

European Geologist

Journal of the European Federation of Geologists



Climate change – Increasing resilience with geological knowledge





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Peer review:
We would like to express a particular thanks to all those who participated in the peer reviewing of this issue and thus contribute to the improvement of the standards of the European Geologist journal. The articles of this issue have been reviewed by Roberto Alvarez de Sotomayor Matesan, Ioanna Badouna, Christos Karkalis and Angelo Statti.

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Foreword

EurGeol. Marko Komac, EFG President

Dear Reader,

Without any doubt, time flies and in front of you is another issue of the *European Geologist*, already the 53rd! For those who follow us regularly, the topic that we're addressing this time is no surprise, while for the rest it could be a good reason to start following the journal. Like in the several past issues, we're again aiming to cover an important issue and potentially the biggest challenge of contemporary society – climate change.

For geologists, the concept of 'climate change' has a special, two-fold meaning. On one hand it is a process that has been present throughout the Earth's history and has notably shaped the evolution of life on this planet's past and, as such, it is a natural process, intertwined with other processes that shape the Earth and its creatures. On the other hand, due to the unprecedented rate of the current climate change our contemporary society is facing huge challenges related to water cycle changes, erosion processes, melting of icecaps, changed weather patterns, biodiversity loss, population migrations, and many more impacts. Our community cannot just silently and indifferently play the role of a bystander. Due to its knowledge about past climate changes, the geological community is one of the most competent to properly support the decision-makers on how to address the problems brought by the climate changes triggered by, or rather caused by the human race. Still, it seems surprising that this issue of *European Geologist* only presents two articles and one editorial. One could attribute this reality to the fact that many facts of today's climate changes are still not understood properly and thoroughly enough to translate them into the practical approaches that this journal mainly presents.

Nevertheless, we bring you two very interesting articles, one dealing with the digital geological data, information and knowledge that represent that basic layer of "Europe beneath our feet" based on which all subsequent geological knowledge is built upon. An important point that the article also emphasises is the harmonisation of geological datasets that enable more effective, holistic and relevant cross-border geoscience related assessments, analyses, and decisions. Remember, geology knows no political borders, hence the decisions need to address the same dimensions!

The second article deals with already locally notable consequences of water/moisture regime changes that reflect in the clay shrinkage and swelling manifested in subsidence or heave and resulting in geotechnical challenges when dealing with foundations design or minimising damage to existing buildings.

In the editorial, EFG Executive Director Glen Burridge challenges the geological community to be more proactive and engaged in the communication of facts, in policy creation and in the decision making related to climate change mitigation, adaptation and minimisation.

No other contemporary challenge applies more to the society than climate change and hence it is not only our capability but also our responsibility to put our knowledge to society's disposal and utilise its possibilities to the full capacity. It's not only for us – it's also or mainly for our descendants and their future.

I'm positive there are many useful results of our community that could be shared with peers, and I invite you to submit them to one of our future issues. Thank you for your devoted engagement and knowledge sharing!



Marko Komac



Editorial

Glen BurrIDGE, EFG Executive Director

For anyone who was in and around COP26 in Glasgow last autumn, they would have been struck by the frequent use of two words on the lips of campaigners and policymakers that carried a powerful punch: 'Earth' and 'Science'.

But I never heard them together.

Only two geoscience organisations – our colleagues at the Geological Society of London (GSL) and Geology for Global Development (GfGD) – were present in the Blue Zone negotiations and then as "Observers".

The long-term future of our society, but also the profession of earth science, is currently being shaped by events like COP, the World Economic Forum and dialogues held by a range of multilateral organisations, such as the IEA, the UN Global Compact, the Glasgow Financial Alliance for Net Zero and, incrementally, by our own industry and professional events.

And we need to be present. We are now at a dramatic and slowly pivoting point in society's relationship with its planet and the unique web of life in which it thrives. As we move from the diagnosis phase of the planet's climate crisis to the mitigation and rebuilding phase, we as earth scientists – and more specifically, geologists – will have a great role to play as major instruments of the solutions that are going to be devised in the decades to come.

In this 53rd edition of the *European Geologist* journal, we explore how this might transpire, the challenges we going to face and how we are going to have to translate our scientific know-how into messages that the public and their representatives understand and will act on.

There will be two great arms to this.

The first will be the technical appreciation of how this planet and its myriad, inter-locking, systems work. This will require a fresh-minded approach among our professional community to transcend boundaries of well-established disciplines, working cultures and technologies. From this change will spring innovation and new horizons for our profession. It is our recognised part of the puzzle.

The second is the ability to Get In The Room where the decisions around our relationship with our planet are being made: to translate the significance of the science, outline the uncertainties and frame the options. This is the arm which is dramatically less familiar to us as natural scientists; it is the art of the diplomat, the policy wonk and the great communicators. This is what we're going to have to get very good at in the years to come as a profession.

At EFG and with our colleagues in our national associations, plus our partners in allied geoscience organisations, I know we are determined to take on this challenge and ensure the voice of geoscience is clearly heard in the arenas where it matters most. We hope that editions such as this will play their part in this progress.

Best regards



Glen BurrIDGE



Pan-European geological data, information, and knowledge for a resilient, sustainable, and collaborative future

Julie Hollis^{1*}, Stephanie Bricker², Dana Čápková³, Klaus Hinsby⁴, Hans-Georg Krenmayr⁵, Phillippe Negrel⁶, Daniel Oliveira⁷, Eleftheria Poyiadji⁸, Serge van Gessel⁹, Sytze van Heteren⁹, Guri Venvik¹⁰

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Many fields of research relevant to climate-change-related policy are grounded in geological sciences – far more than is generally recognised by the public or policy makers. These fields include management of marine environments, urban development, ground-water, landslide risk, understanding the geochemistry of soils and water, and securing raw materials. Through the concerted collaborative efforts, over many years, of EuroGeoSurveys – the Geological Surveys of Europe – national datasets bearing on these and other areas have been harmonised at European scale and delivered through an online digital platform, the European Geological Data Infrastructure. This vast store of baseline data, information, and knowledge is crucial for informed pan-European decision making and is considered the core of a future Geological Service for Europe.

De nombreux domaines de recherche pertinents pour les politiques liées au changement climatique sont fondés sur les sciences géologiques – bien plus que ce qui est généralement reconnu par le public ou les décideurs. Ces domaines incluent la gestion des milieux marins, l'aménagement urbain, les nappes phréatiques, les risques de glissement de terrain, la compréhension de la géochimie des sols et de l'eau et la sécurisation des matières premières. Depuis de nombreuses années, grâce aux nombreux efforts de collaboration concertés des EuroGeoSurveys – les services géologiques d'Europe – les ensembles de données nationaux portant sur ces domaines (ainsi que d'autres) ont été harmonisés à l'échelle européenne et fournis via une plateforme numérique en ligne – le European Geological Data Infrastructure. Cette vaste banque de données, d'informations et de connaissances est cruciale pour une prise de décision paneuropéenne éclairée et est considérée comme le cœur d'un futur service géologique pour l'Europe.

Muchos campos de investigación concernientes con el cambio climático están relacionados con las ciencias geológicas – mucho más de lo que es reconocido por el público o por los responsables de políticas gubernamentales. Estos campos incluyen manejo de ambientes marinos, desarrollo urbano, aguas subterráneas, riesgos de deslizamientos, la comprensión de la geoquímica de suelos y agua y el aseguramiento de materias primas. A través de esfuerzos colaborativos mancomunados por muchos años de EuroGeoSurveys – Servicios Geológicos Europeos – se han integrado a escala europea, bases de datos nacionales, relacionadas con estos temas y otras áreas, para que estén disponibles en plataformas digitales en línea a través de la agencia Geológica de Datos de Infraestructura Europea. Este gran almacenamiento de datos es base de referencia, información y conocimiento, crucial para la toma de decisiones técnicas a nivel pan-Europeo y se considera el núcleo central, clave para un futuro Servicio Geológico Europeo.

Introduction – a foundational geological data infrastructure

Climate change is generating sharp changes in environmental conditions on geologically short time

scales, requiring decision-making that is resilient in the face of such rapid changes at local to Pan-European and even global scale. Key to developing resilient decision-making that protects society and nature (Lewis and Maslin, 2015; Steffen *et al.*, 2018), and keeps

Earth within planetary boundaries (Steffen *et al.*, 2015; Lade *et al.* 2020) is the digital infrastructure and data that will support the EU's goal of climate neutrality by 2050, the Green Deal (European Commission, 2022), and the UN sustainable development goals (United Nations, 2022). Easy and efficient access to digital data is crucial for: i) prioritising competing uses of the subsurface, ii) sustainable use of subsurface resources, iii) integrated surface and subsurface spatial planning, iv) sustainable use of groundwater as a crucial part of the hydrological cycle connecting surface and subsurface freshwater resources (Gleeson *et al.*, 2020), and v) adaptation to climate-related extreme events (Quevauviller, 2022). The EU's digital strategy aims to strengthen its digital sovereignty and set standards, with a clear focus on data, technology, and infrastructure. One important component of the required digital data and data infrastructure is geological data, which can directly inform on such diverse climate-impacted areas as our changing urban and built envi-

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ronments (including infrastructure such as railways and roads), risk of landslides and land subsidence, agriculture and food, clean water, ecosystems and biodiversity, and the development of sustainable and renewable energy and clean technologies, honouring the water-energy-food nexus (Bazilian *et al.*, 2011; de Roo *et al.*, 2020). It is also crucial that these data are accessible, current, and harmonised at European scale and include near real-time data for early warning of events that will have significant societal impacts, such as combined groundwater and surface water flooding following climate-related extreme events (Hughes *et al.*, 2011; Quevauviller, 2022).

The need for up-to-date pan-European geological data that is findable, accessible, interoperable and reusable (FAIR, Wilkinson *et al.*, 2016) has been addressed by EuroGeoSurveys (EGS) by developing a common sustainable European Geological Data Infrastructure (EGDI, 2022). The main priority is to provide the European Commission and other users with high quality, trusted, borderless, digital public services, facilitating free access to multinational geological data, monitoring and modelling results and harmonised data, information and knowledge at European level – data that are derived from the Geological Survey Organisations' national databases and that are of high value when assessing current and future climate change impacts. Great efforts by EGS are being made to harmonise and make use of a large variety of important geological data in new and innovative ways and make the data available in accordance with INSPIRE and other relevant standards.

For almost two decades, EGS members have collaborated within many EU projects focused on harmonisation of geological data across Europe. In 2014, an analysis showed that the EU had funded geological data harmonisation projects, providing support of several hundred thousands of euros, but that only a small fraction of the results were still available online, a few years after the projects had ended. EGS therefore decided to establish EGDI, first launched in 2016. The first version consisted of a web GIS, dedicated GIS viewers for specific geological topics, numerous distributed web services, a metadata catalogue, and a database of pan-European harvested data. It gave access to over 600 layers from 13 projects. EGDI has since provided a pipeline of data, information, and knowledge through which the geological surveys connect strategically and technically with the wider European Research and Digital landscape. In 2018, the Horizon

2020 ERA-NET on Applied Geosciences (GeoERA) was launched with 15 projects, including an information platform project developing common map viewers for the 14 projects within geoenergy, groundwater and raw materials and generating many local to pan-European datasets (EGDI, 2022). EGDI is the platform to safeguard, harmonise and disseminate all of this information. Through a dedicated project in the GeoERA program (GIP-P), EGDI significantly expanded to include a document repository, a search system, a 3D database, vocabularies, a user-support system and eLearning platform. When GeoERA ended in October 2021, EGDI made available the results from a total of 37 projects covering on- and offshore geology, raw materials, geoenergy, groundwater, geohazards, geochemistry and geophysics.

Future plans focus on the further development of EGDI into a knowledge infrastructure, continuing the harmonisation and standardisation effort, but also innovation around how subsurface information is processed. Improving the accessibility and quality of the results of future geological research will ensure the usability and long-term sustainability of the EGDI. Data and services will also connect EGDI to other infrastructures (e.g. EMODnet (<https://emodnet.ec.europa.eu/en>), EPOS (<https://www.epos-eu.org>), WISE (<https://water.europa.eu>)), bringing geological data, information, and knowledge to other domains and vice versa.

The ultimate goal of this EGS work is to establish a subsurface knowledge network that provides useful and up-to-date information to decision-makers and the scientific community, and that feeds European data platforms. Furthermore, this network is open for collaboration with stakeholders to further build the infrastructure, through the addition of data and interpretations. The network will be the cornerstone of the Geological Service for Europe – a collaborative effort and vision of the European Geological Surveys through EGS. To achieve this goal, the quality and reliability of the data and information (the content) needs to be ensured and the technical infrastructure (EGDI) underlying the data and information must be kept up to date. To ensure the accuracy and timeliness of EGDI content, a permanent network of thematic experts from Geological Survey Organisations will be organised, focusing on the systematic creation, control and continuous updating of information, metadata and data in EGDI in collaboration with stakeholders. In this contribution, we present examples of the combined efforts of EGS

through GeoERA and other projects, covering diverse geological disciplines relevant to public policy-making, and delivered through EGDI.

Marine management

Since 2009 all of Europe's geologic surveys involved in seabed mapping have worked together in producing accessible and harmonised data and data products on the seabed surface, its shallow subsurface, seabed geomorphology, coastal behaviour, marine-geological events, hydrocarbon and mineral resources, and submerged landscapes. These data are provided through the EMODnet Geology portal, developed through participation of the EGS' Marine Geology Expert Group (MGEG) in the European Marine Observation and Data network (Vallius *et al.*, 2020; Moses and Vallius, 2020).

The work of MGEG fits neatly within Europe's aim to be the first climate-neutral continent. In support of Blue Growth and the Biodiversity Strategy, reliable maps of the surficial seabed substrate provide Europe with information on habitat suitability. They help explain the location of benthic species and communities and predict where they could thrive (Kaskela *et al.*, 2019). The deeper geology of the sea-floor subsurface is critically important in decarbonising the energy sector (Guinan *et al.*, 2020). It determines how suitable an offshore area is for wind-turbine foundations, for trenching energy cables, and for capturing carbon. The Strategy on Adaptation to Climate Change relies on knowledge of coastal behaviour and expertise on geohazards at the land-sea boundary. Awareness mapping identifies areas with specific geological conditions that may render them susceptible to unwanted effects of climate change (Ryabchuk *et al.*, 2020). Awareness mapping is also needed to optimise preventive and remedial coastal-zone management policies. We especially need reliable data and expertise to prioritise conflicting use of the subsea. Aggregates and marine minerals are necessary for the energy transition, but minimising the environmental impact of their extraction requires broad-scale information allowing policy makers to make those prioritisations (Terrinha *et al.*, 2019). Study of the marine environment also allows us to learn from the past. In mapping drowned European landscapes, we may discover, for instance, how sea-level rise affected Stone Age societies: adaptation to climate change is not a concept invented in the twentieth century.

Importantly, EMODnet Geology is

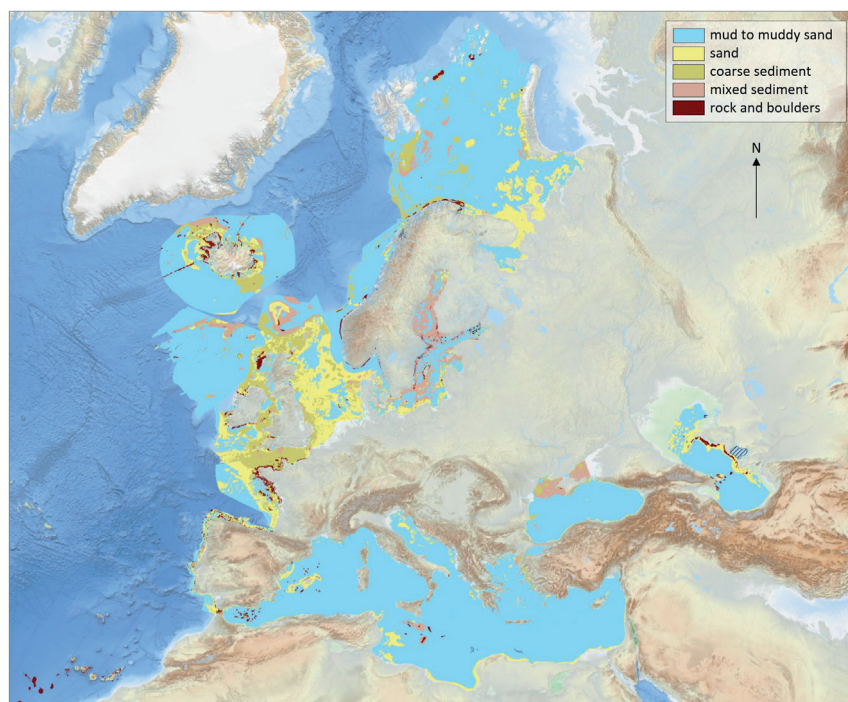


Figure 1: Portal view of EMODnet Geology map (Map viewer – Geology (emodnet-geology.eu)), showing type of sediment or rock exposed at the seabed.

embedded in a broader programme that addresses bathymetry, biology, chemistry, human activities, physics, and seabed habitats (Martín Míguez *et al.*, 2019). These disciplines have been pooling their knowledge and resources. One example is the digital terrain model of EMODnet Bathymetry, which has been instrumental in generating a geological data product on geomorphology that interprets the purely descriptive water-depth model in terms of formative processes and anticipated future behaviour. Adding these explanatory and predictive elements is a key step forward. The ecological significance of geological information on the seabed substrate has helped EMODnet Seabed Habitats achieve their pan-European aspirations. Due to much better coverage of geological than biological information, rock and sediment type are the proxy of choice in modern-day marine habitat mapping (Figure 1). These and other success stories stimulate further cooperation. They also show policy makers and other end users the added value of joint output, as illustrated and facilitated by the Commission's European Atlas of the Seas (https://ec.europa.eu/maritimeaffairs/atlas/maritime_atlas).

Urban management

Europe is a highly urbanised region with urban populations ranging from 55% in e.g. Slovakia, up to 98% in Belgium. With high

urban populations, increased urban expansion and densification of services, Europe's towns and cities are increasingly vulnerable to climate risks: urgent action is demanded to mitigate and adapt to the impacts of climate change. UN Sustainable Development Goal (SDG) 11 (Sustainable Cities and Communities) and the New Urban Agenda (United Nations, 2017) are clear in their ambition for towns and cities to fulfil their social and ecological functions, and to be resilient and sustainable in an uncertain climatic future. Urban geology – at the intersection of natural-built-social systems – and wider management of urban underground space are critical in the delivery of SDG 11 and climate adaptation measures (Admiraal and Cornaro, 2016). Delivering climate-resilient cities will, however, place competing demands on subsurface natural systems and resources, whether the space is utilised as a shallow geothermal energy source, to provide energy storage and house urban heat networks, to support urban green-blue infrastructure, to maximise the infiltration of water to the ground through sustainable drainage systems, or to provide cool spaces underground as urban temperatures rise (Bricker, 2021). This is reflected in the priority urban geology topics identified by EGS, including low-carbon energy, resource optimisation, nature-based solutions, hazard and risk management, and digital data workflows.

Addressing these needs, geologists

across Europe have been working in collaboration with urban planners across 24 countries, initially through the EU COST Sub-Urban Action (van der Meulen *et al.*, 2016), to ensure that geological data, evidence, and information are embedded in urban planning and place-making. A recent survey (2020) of 20 of the EGS member geological surveys shows that all provide geological datasets suitable for application at the urban scale (1:50,000 or larger scale). Fifteen countries offer 10 or more urban-scale geological datasets (e.g. hydrogeology maps, subsidence hazard, geoheritage sites), with some offering bespoke urban planning packs or data tools such as maps showing suitable locations for sustainable urban drainage systems (SuDS) (Dearden *et al.*, 2013). Seventy per cent of the geological surveys undertake 3D urban geological modelling. Over and above data provision, the Sub-Urban Action focused on the development of good practice guidance in relation to subsurface planning, data management, 3D modelling, urban groundwater and geothermal systems, and geochemical mapping. Bridging the gap between planners and subsurface specialists (Dick *et al.*, 2017), geologists demonstrated the value of having an integrated 3D urban ground information model, which provides an enhanced understanding of the geological character and physical properties of the ground. This underpins a subsurface masterplan and identifies options for resilient land uses such as nature-based solutions. Applying these geological data-models, geologists in partnership with urban practitioners have, e.g., evaluated the effectiveness of SuDS for flood management (Archer *et al.*, 2020; Lentini *et al.*, 2021) and investigated the use of SuDS to help stabilise groundwater levels and lower subsidence risk (Venvik *et al.*, 2020). Urban planners have used the enhanced subsurface understanding to realise the multiple environmental and socio-economic benefits of SuDS (BiTC, 2018) and implement nature-based climate adaption measures (e.g. [Connectingnature.eu/Glasgow](https://connectingnature.eu/Glasgow)).

The lack of legislation at both national and European level creates challenges for the management of the subsurface (Volchko *et al.*, 2020). Although the geological subsurface is diverse across Europe, the human needs and the facilities inserted into the subsurface are common, such as tunnels, parking, etc. A unified, pan-European understanding of subsurface FAIR-data would promote the goal of data-driven decision making and the possibility for Digital Twins. An example is the EU Water

Framework Directive (Water Framework Directive, 2000) upon which a subsurface framework could be based. Although time-consuming to co-ordinate and implement, common legislation regarding the quality and quantity of waterbodies, above and below ground, has been successfully implemented across Europe. Similar directives concerning the subsurface, especially in cities, would enhance data recovery and re-use, thereby reducing risks and making cities more resilient.

Sustainable Geo-Energy Resources and Capacities

Energy is vital to almost all aspects of our society, such as heating our homes, producing food and resources, manufacturing feedstock and derived products, transport, serving our ever-growing digital needs and much more. However, our energy consumption poses two major challenges. On the one hand, our huge dependency on fossil fuels (oil, natural gas, and coal) leads to rising atmospheric CO₂ concentrations and subsequent climate change. On the other hand, there is a decline in domestic energy production and, as a result, we become more dependent on suppliers outside Europe. These challenges, among others, are addressed in the European Green Deal agenda by increasing our capacities for domestic renewable energy generation, reducing energy consumption and preventing emissions of CO₂ and other greenhouse gases. The subsurface provides capacities and possibilities that match the scale of society's needs. The main technology options are:

- Shallow and deep geothermal energy to support low-carbon heating demand in the built environment, agricultural sector, industry sector and power generation sector.
- Storage of CO₂, which is essentially the only option to effectively reduce emissions while we are still dependent on fossil fuels and to enable negative emissions in combination with low-carbon energy generation
- Storage of sustainable energy carriers in the form of hydrogen, green gas, heat and cold, compressed air, and other mechanical forms of energy. This is needed to balance increasing shares of variable renewable energy (wind/solar) against seasonal consumption, increase renewable energy efficiency and secure affordable

energy in periods of supply disruption (e.g. reduce potential economic impacts from extremely high energy prices or energy shortages in industry).

- Domestic production of natural gas is still regarded as important to bridge the energy transition during the coming decades and to slow down our increasing import dependency.

Six GeoERA Energy projects deliver FAIR information, harmonised methodologies, and strategies for identifying, managing and responsibly developing the above resources. The main objectives and scope included (i) harmonised prediction of geo-energy resources and storage capacities; (ii) identification of synergies and potential bottlenecks, such as hazards and environmental impacts; (iii) deployment of geological information in state-of-art decision support and subsurface management and planning tools; and (iv) improved dialogue with stakeholders, societal organisations and the public. The following projects have successfully contributed to these objectives:

- MUSE – A novel information platform and stakeholder tools to enable and responsibly manage and deploy shallow geothermal potential in urban areas
- Hotlime – Harmonised methods and information to unravel the potential for development of deep geothermal plays in Europe and reduction of exploration risks
- GARAH - Capitalising on information and knowledge from the Oil & Gas industry to unlock the hydrocarbon potential in EU seas and options for CO₂ and energy storage
- HIKE - A new state-of-art database for analysing and disseminating information on faults, including methods to assess hazards and impacts from geo-energy uses
- 3DGEO-EU - State-of-the-art methods and strategies that pave the way towards a harmonised 3D digital twin of Europe's geology and subsurface energy resources
- GeoConnect3d – A first-of-its-kind framework and tools to support subsurface management and stakeholder dialogues, focusing on different themes including geo-energy uses.

The GeoERA Energy projects deliver a stepping stone for the upcoming Geo-

logical Service for Europe, which will focus on developing key knowledge and pan-European databases and atlases that will extend the knowledge and information base to responsibly unlock and develop geothermal energy, permanent storage of CO₂ and temporary storage of sustainable energy carriers.

Water Resources

Sufficient groundwater of good quality is extremely important for societies, ecosystems, and biodiversity and the Water Framework and Groundwater directives stipulate that all EU member states must assess and report the status of European groundwater bodies (European Environment Agency, 2022). The groundwater chemical and quantitative status must be assessed based on good status objectives for legitimate uses (e.g. drinking water) and groundwater dependent terrestrial and aquatic ecosystems including coastal and marine waters (Hinsby *et al.*, 2008, 2011, 2012). Too much or too little water endangers food production, biodiversity, the built environment, and may result in floods, droughts, landslides, land subsidence, and other geohazards. Migration of polluted groundwater may also jeopardise the quality of even deeper aquifers supplying old pristine drinking water to European citizens (Broers *et al.*, 2021; Hinsby *et al.*, 2001); and salt water intrusion into coastal aquifers may do the same (Hinsby *et al.*, 2011; Werner *et al.*, 2013).

In the GeoERA programme, the Water Resources Expert Group (WREG) of EGS investigated groundwater quantity and quality issues related to natural processes, human activities, and climate change (GeoERA, 2022). The aim was to improve the basis for informed decision-making regarding protection of, or related to, (i) groundwater quantitative and chemical status; (ii) groundwater legitimate uses; (iii) groundwater-dependent terrestrial and associated aquatic ecosystems and biodiversity; (iv) the groundwater ecosystem itself; (v) ecosystem services; and (vi) climate and global change mitigation and adaptation. The GeoERA groundwater projects provide new, important FAIR data, accessible through EGDI for improved water resources management in Europe. This data will improve our understanding of the subsurface and is being used to develop efficient tools, e.g. for water resources mapping, monitoring and modelling, climate change impact assessment, mitigation and adaptation. The groundwater projects were:

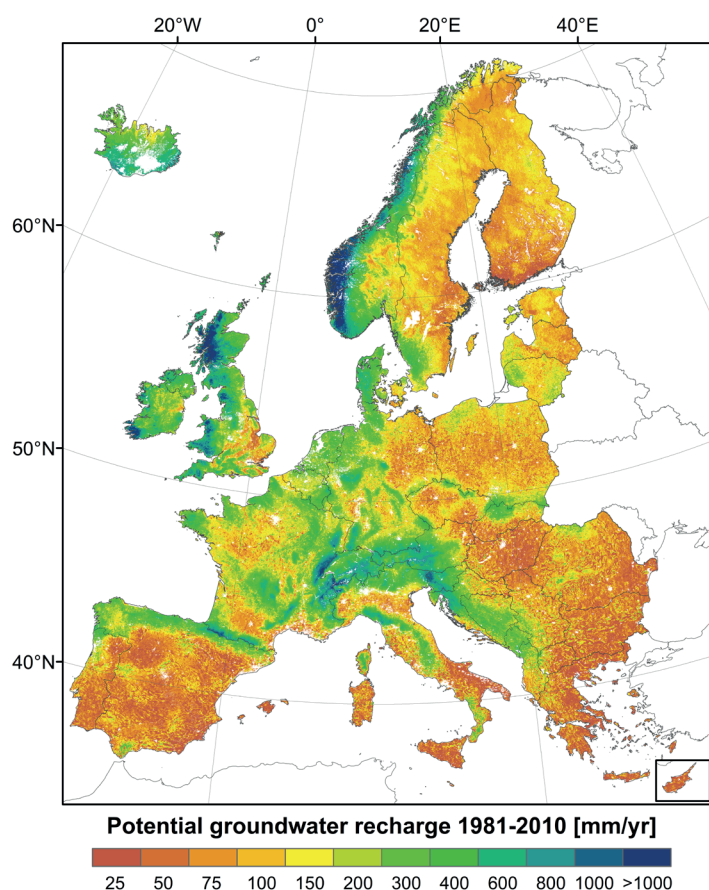


Figure 2: Long-term average pan-European potential groundwater recharge map (1981–2010) developed based on local and national recharge estimates, satellite data (e.g. Stisen *et al.*, 2021) and machine learning (Martinsen *et al.*, 2022) (note that Cyprus is included in the inset, bottom right). The data are relevant for (e.g.) integrated groundwater-surface water models simulating and assessing climate change impacts on European water resources, future risk of groundwater and surface water flooding, nutrient loadings to groundwater and associated aquatic ecosystems (Hinsby *et al.*, 2008, 2012), and assessments of climate change impacts on the water-energy-food-ecosystem nexus (WEFE, 2019).

- HOVER – “Hydrogeological processes and geological settings over Europe controlling dissolved geogenic and anthropogenic elements in groundwater.”
- RESOURCE – “Resources of groundwater, harmonised at cross-border and pan-European Scale,” including integrated studies in two transboundary aquifer settings, Belgium-Germany-the Netherlands and Poland-Lithuania, and a new pan-European groundwater resources map that includes information on volumes, age and quality (salinity).
- TACTIC – “Tools for assessment of climate change impact on groundwater and adaptation strategies,” including e.g. a pan-European groundwater recharge map (Figure 2), projections

of groundwater levels in different climate scenarios, and salt water intrusion issues in coastal aquifers

- VoGERA – “Vulnerability of shallow groundwater resources to deep sub-surface energy-related activities,” including a decision support tool/Excel workbook for vulnerability assessments available via the VoGERA map viewer on EGDI and a range of conceptual models relevant for these assessments.

The main impacts and services of the four GeoERA groundwater projects include: improved access to downloadable groundwater quantity and quality data on a local to pan-European scale; state-of-the-art tools to support sustainable decision making in relation to the water-food-energy-ecosystem nexus; tools for assessment of climate change impacts; mitigation and adaptation

strategies, drought and flood risks, etc. (Figure 2); and opportunities for private companies and research institutions to collaborate and develop new groundwater add-on services to EGDI. The data and tools provide valuable information and assessments for EU and UN policy implementation and development including the European Green Deal (European Commission, 2022), the UN Sustainable Development Goals (United Nations, 2022) and the UN Framework Classification for Groundwater, which is included in the new UN Resource Management System together with framework classifications for other subsurface resources, etc. (UNECE 2021a, b).

Landslide risk

Geohazards (geology-related natural hazards) have great socioeconomic impact and are being addressed by the Sendai Framework for Disaster Risk Reduction 2015–2030 (United Nations, 2015). Although many geohazards, such as earthquakes, are widely recognised and people are aware of seismic risk, this is not the case for a large subcategory of geohazards – those related to ground instability: landslides, subsidence, and sinkholes. A pan-European database and the resulting maps could certainly help landslide hazard management on European, national, and regional scales, being also useful to perform multi-hazard analysis in areas with high seismic hazard. For this reason, in 2017, the Earth Observation and Geohazards Expert Group (EOEG) of EGS analysed the landslide databases of the Geological Surveys of Europe (Herrera *et al.*, 2017), focussing on their completeness and interoperability.

A total of 849,543 landslide records for 24 countries were classified as slides (36%), falls (10%), flows (20%), complex slides (11%), and others (24%). The majority of records for each landslide type are mapped with the same features at 1:25,000 or greater, allowing generation of European-scale maps for each landslide type. However, the locational accuracy of every landslide has not been evaluated using the same procedure and should be harmonised (e.g., using the procedure of BRGM, BGS or ISPRA). Based on the additional information available for most of the landslide databases, the European-scale susceptibility assessment for each landslide type seems justified. However, information necessary for hazard and risk analysis is scarce (<40%) and heterogeneously distributed across countries. Therefore, European-scale hazard and risk assessments are difficult to achieve.

A landslide density map was produced (Figure 3) showing, for the first time, 210,544 km² of landslide-prone areas in Europe. A comparison of the LANDEN map (Figure 3) with the European landslide susceptibility map (ELSUS 1000 v1) highlights gaps in the existing landslide databases and the variable landslide strategies adopted across Europe. In some countries, landslide mapping is systematic. In others, only damaging landslides are recorded. In others still, landslide maps are only available for certain regions or local areas. Moreover, in most countries landslide databases from the Geological Surveys co-exist with others (at variable scales and formats) managed by a variety of public institutions.

Another survey carried out among twenty-one national and eight regional Geological Surveys analysed existing legislation across European countries related to the integration of landslide hazard into urban planning (Mateos *et al.*, 2020). The survey revealed that almost half of the ten participating countries have no legal guidance in the National Land Bill to stipulate consideration of landslides in urban planning practices, and mapping tools are often not adapted to a standard required to inform sustainable development. Furthermore, the analysis showed that there is a wide range of laws and large heterogeneity in mapping methods, scales and procedures. A relevant deficiency detected in many countries is the lack of landslide maps at a detailed resolution for urban planning.

To assess the impact of landslide hazard in Europe, EOEG gathered information from the geological surveys and created an inventory and database of damaging landslides for a three-year period (2015–2017). The data focused on just few related parameters, as the purpose was to understand triggering factors and impacts on European countries: landslide typology; spatial distribution; triggering factor; fatalities and injuries; and damages. For this three-year period, 3,846 damaging landslides occurred in 19 European countries, including Switzerland and Ukraine (but not Denmark, Germany, Norway, Slovakia or Sweden). 143 landslides caused 39 fatalities and 155 people were injured. Most landslides (69%) were triggered by episodes of intense or long-lasting rainfall, or both. Croatia, Greece, and Italy recorded 43 landslides triggered by earthquakes (1.1% of the total). For the remainder (around 30%), the triggering factor is either not registered (some countries do not keep records of triggering factors) or unknown (Mateos *et al.*, 2020).

If we consider that more intense floods

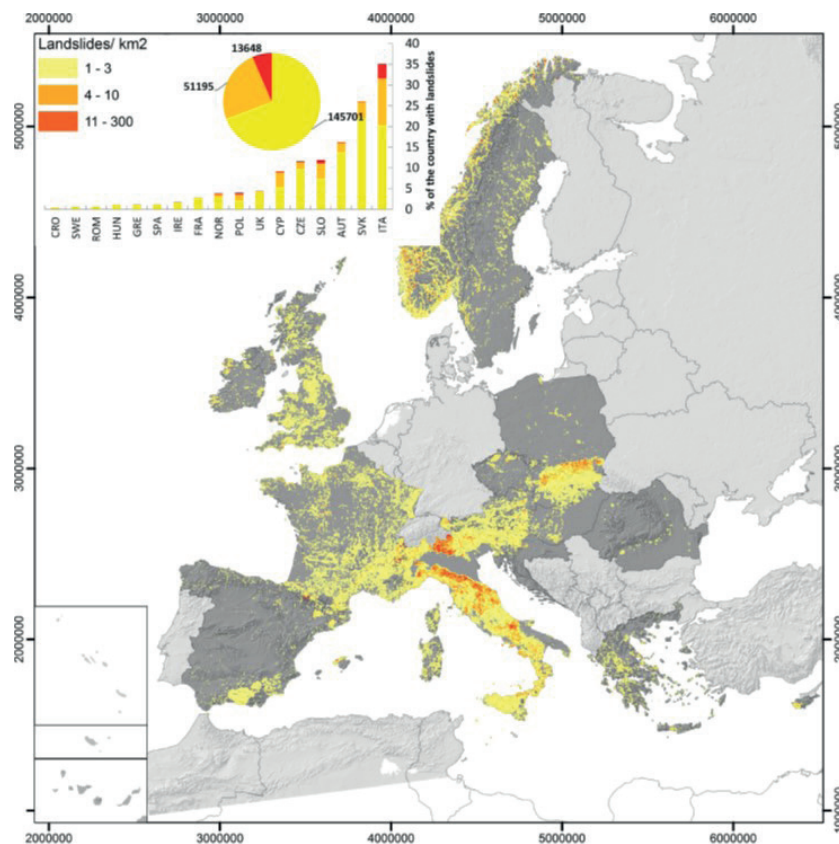


Figure 3: The LANDEN map – a landslide density map for Europe, based on landslide data from 24 countries and showing 210,544 km² of landslide-prone areas.

and storms will result from climate change (European Environment Agency, 2021), the number of landslides will also increase. There are many documented European cases of long rainy periods that triggered many landslides over large areas (Multiple Occurrence Regional Landslide Events, or MORLEs, defined by Crozier, 2005). An example of this abnormal situation took place on Mallorca (Spain) in the period 2008–2010, when a combination of persistent precipitation and low temperature caused an unusual number of slope failures. This had a great impact on the regional economy, which revolves exclusively around tourism (Mateos *et al.*, 2012). 18 MORLEs during the past 10 years were reported by 11 Geological Surveys (Mateos *et al.*, 2020), with a total of approximately 150 fatalities and severe economic impacts. Most MORLEs are related to extreme rainfall episodes, and usually associated with other major natural disasters, such as flooding. MORLEs are not well recognised publicly and the media overlook their effects. Meanwhile, landslide risk, and MORLEs, will increase due to climate change, making the management of events more difficult as the civil protection authorities will have to

cope with concurrent landslides affecting large areas.

Soil geochemistry

Regional geochemical mapping highlights continental scale anomalies or patterns in surface- or groundwater and soil. Such maps (derived from geochemical surveys) provide invaluable information about natural and human-induced concentrations of chemical elements in the near-surface environment (Demetriades *et al.*, 2010). This is known as the 'critical zone', where we live, grow crops, raise livestock, and from which we extract our drinking water, and other raw materials, including mineral wealth. To recognise and understand changes in natural systems, we need well-characterised and current knowledge of a range of baseline levels.

Collaborative efforts to geochemically map Europe have been ongoing for decades through EGS and its precursor organisations. Geochemical mapping on the European scale started in 1985 when the WEGS (Western European Geological Surveys) established a Working Group on "Regional Geochemical Mapping", succeeded by the Geochemistry Task Group implemented by

the FOREGS (Forum of European Geological Surveys) in 1993. Geochemical baselines were urgently needed in Europe at that time because environmental authorities in most countries were defining limits for contaminants in soils for different land use purposes and to contribute to the preparation of the future EU Soil Protection Directive (European Commission, 2002, 2006). Based on stream water, stream sediment, topsoil (0–25 cm), subsoil (>75 cm) and floodplain sediment samples from approximately 800 drainage basins within 26 countries and an area of 4.25 million km² in Europe, the geochemical mapping of Europe project from FOREGS was carried out from 1997 to 2006. This yielded the first geochemical atlas of Europe (Salminen *et al.*, 2005; De Vos, Tarvainen *et al.*, 2006), a harmonised pan-European or Global geochemical ‘baseline’. Between 2008 and 2014, the EGS Geochemistry Expert Group (GEG) conducted the GEMAS project, covering 33 European countries and an area of 5.6 million km² (Reimann *et al.*, 2014a, b). GEMAS documents, for the first time, the concentration of almost 60 chemical elements, and the parameters determining their availability and binding in agricultural and grazing land soils at the scale of a continent. In GEMAS, the two different sample materials, ploughed soil (0–20 cm) and grazing land soil (0–10 cm), taken at different locations at a density of 1 site/2500 km² across Europe, deliver very comparable distribution maps for most elements. The results confirm that low sample density mapping results in robust geochemi-

cal maps. Natural and/or anthropogenic origins for the elements in the soils can be investigated at the continental scale (Reimann *et al.*, 2018), as is now realised over other continents (Smith *et al.*, 2013; Wang *et al.*, 2015; Reimann and Caritat, 2017). For such continental scale mapping, a high quality geochemical baseline data must be established, requiring standardised sampling, sample preparation and analytical methodologies to obtain a consistent and harmonised dataset. This was done for the GEMAS project, giving for the first time more than 50 chemical element concentrations and physical properties.

Geology, i.e. the rocks from which the soils were derived, plays a key role in determining the map patterns. Many chemical elements are dominated by anomalies related to single ore deposits or metal provinces. Soil developed on the sediments of the last glaciation, on chalk and limestone, granite, alkaline intrusions, greenstone or black shale, all have their own geochemical signature that can be detected on the maps. As examples, silicon in the agricultural soil samples displays high concentrations in northern central Europe, over the thick silica-rich sediments of the last glaciation, whereas calcium displays high concentrations over areas underlain by chalk and limestone, mainly in southern Europe (Figure 4).

The elements associated with human activities are marked by elevated element concentrations in the agricultural soil samples taken in the vicinity of some big European cities (e.g. London, Paris, Rotterdam) and in some cases also small ones

(e.g. Verdun, in France, is marked by a high lead anomaly due to material derived from World War One battles). However, an anthropogenic impact is difficult to detect at the mapping scale of the GEMAS project. The locations of most metal smelters or coal fired power plants, for instance, remain invisible on the maps. Many of the high values observed are actually related to natural metal occurrences or to specific rock types that are enriched in these elements. The human impact on the quality of the agricultural soils remains low at the continental scale.

Many trace elements are important for the health of plants, animals and humans. While very few soil samples reach concentrations where toxicity may become a concern, more than 10% of the samples contain such low concentrations of certain elements that deficiency is an issue for optimum plant and animal health and productivity – possibly an issue warranting significant attention at European scale.

GEMAS approaches soil geochemistry from different perspectives. In addition to the approach based on the interest of the elements studied (e.g. pollutants, nutrients, natural resources, role of climate), the weathering processes from rock to soil, the health aspects via the presence or absence of certain elements, or even the approach of the very recent criticality assessment of certain elements are at the heart of GEMAS. This geochemical atlas at the European scale, with the low-density approach, can be used for effective land use planning, e.g. prioritisation and management of mineral exploration, agriculture and forestry, animal

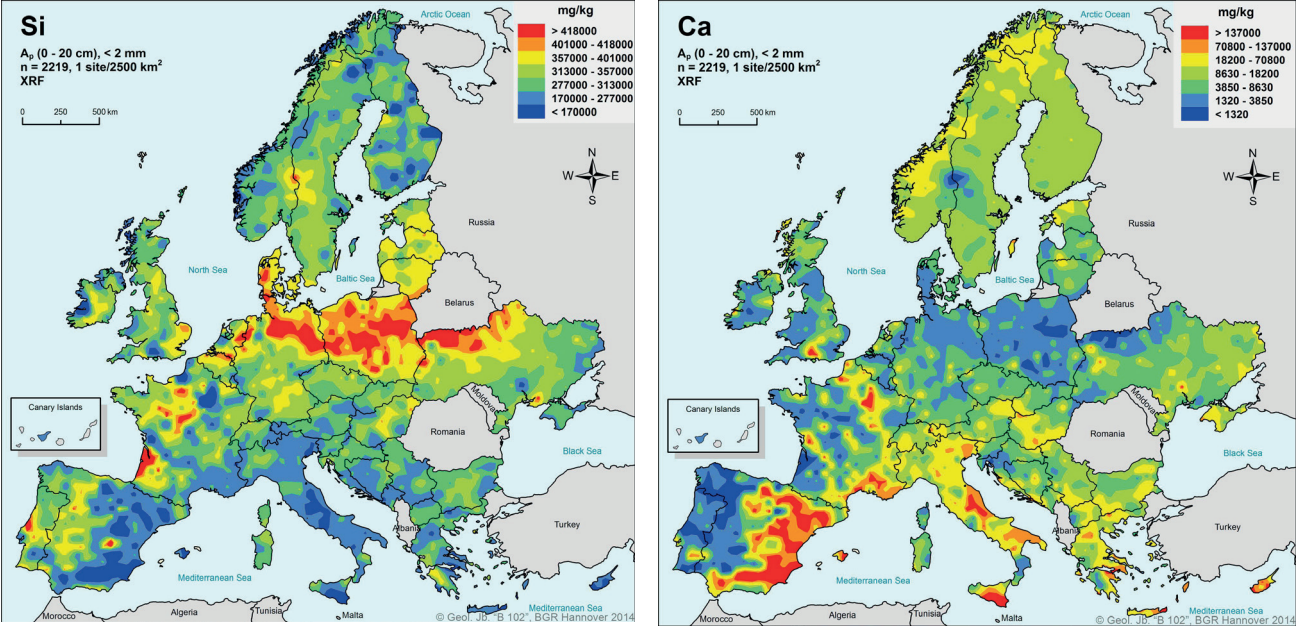


Figure 4: Geochemical map for (a) Si and (b) Ca total concentrations in ploughed agricultural soil (A_p , $n=2108$) (XRF results). Interpolation by kriging, range = 1,000 km, and search radius = 300 km. Modified from Reimann *et al.* (2014a, b).

husbandry, land use and environmental policies, health-related research, and construction adaptation of towns. Policy, which plays a key role, is becoming more holistic and the trend is to address the whole soil system, for which these baseline data are fundamental.

Minerals and critical raw materials

The 19th and 20th centuries saw a shift from agrarian to industrialised societies, together with a growing world population and changing consumption patterns. These led to increasing global demand for raw materials. Today, non-energy minerals underpin modern economies, being essential for manufacturing and renewable energy (e.g., Commission of the European Communities (2008); de Oliveira *et al.*, 2020a, 2020b, 2021; Wittenberg *et al.*, 2020a, 2020b; IEA, 2021), and domestic production is a key factor in improving the security of supply of raw materials to the EU (European Commission, 2018). Projections of future trends indicate that resource use could double between 2010 and 2030, mostly driven by demand in developing regions (European Commission, 2016). And while the EC's Blue Growth strategy estimated that by 2030, 5% of the world's minerals, including cobalt, copper and zinc, could come from a new region – the ocean floors (SWD(2017) 128 final) – the crucial question is whether supply is adequate to meet future demands. Access to sustainable mineral resources is key for the EU's resilience in achieving the goals of the EU Green Deal. Achieving resource security requires action to diversify supply from both primary and secondary sources, reducing dependencies and improving efficiency and circularity, including sustainable product design. This is true for all raw materials but is vital for those raw materials that are considered critical for the EU.

Access to mineral resources is only possible with risky, long-term investments in exploration and a reliable knowledge base. The stronger and more complete the knowledge base, the less risky investments and decision-making processes become. Across Europe, significant investments have been made in building the foundations of this knowledge base with several collaborative key EGS projects, delivering accurate and homogenised data. Efforts commenced with EuroGeoSource; the first EU data platform that delved into the complex issue of INSPIRE compliancy, followed by Minerals4EU. The latter led to the first European homogenised dataset, followed by

the MINTELL4EU project, which extended the spatial coverage and harmonisation. MINTELL4EU provides a basic overview of available European raw materials data, visualised through EGDI. However, focused EC initiatives, based on concerns for data on critical raw materials (CRM), led to specific projects to highlight and update CRM datasets. The PROMINE project created the first comprehensive CRM dataset and was used to produce the first CRM map of Europe (Bertrand *et al.*, 2016).

The dominating issue of the CRM has played an important part in establishing potential CRM sources in Europe that could diminish dependency on imports. The predominate use of the rare earth elements (REE), in particular the use of the heavy REE in green energy generating technologies, and the lack of potential EU sources of these elements, forced the EC to investigate further. Hence, between the publication of the first and second CRM lists, the European Rare Earths Competency Network, a precursor to the European Raw Materials Alliance, was established to deal with (a) opportunities and roadblocks for primary supply of REE in Europe, (b) European REE resource efficiency and recycling, and (c) European end-user industries and REE supply trends and challenges. Further research into REE was carried out under the project EuRare, for the “Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits”.

The EMODnet Geology project aims since 2014 at providing harmonised catalogues on marine minerals, as one of several EMODnet projects with the aim of strengthening blue growth in Europe. The latest, and largest, pan-European collaborative effort on raw materials is GeoERA, which comprises four raw materials projects (FRAME, MINDeSEA, MINTELL4EU and EUROLITHOS), which evaluated, in a comparable way, the European Raw Materials, and which are visualised in accessible databases, maps and scientific publications, delivered through EGDI. EGDI will form the basis for further knowledge-based, better raw materials decision making for legislators and prospectors alike.

Harmonisation of geological data

Underpinning nearly all applied geological products and data, including all of the disciplines already discussed here, is the requirement for both onshore and offshore geological maps, map datasets, and 3D-models. For example, the INSPIRE-directive designates Geology as a key

dataset needed for the Groundwater and Soils Directives, GMES and GEOSS. Additionally, today's economic, environmental, and planning issues in the fields of clean energy supply, mineral resources, and land use – all of them serving to mitigate the effects of climate change – require access to precise geological basic information on the subsurface. As any successful surgery is based on anatomical knowledge of the (human) body, any operation related to the subsurface should be based on “anatomical” geological knowledge of the Earth's crust. Presently, many applied geology projects suffer from deficient or outdated geological basic information. If this is due to data gaps, which is frequently the case, the problem should be solved mainly on national level by implementing or strengthening existing geological mapping programs in 2D and 3D. However, the valuable geological data already held by the European geological surveys are in some cases difficult to discover, understand and use efficiently due to lack of standardization.

An important contribution to solving this problem was the OneGeology-Europe project, which aimed to create a dynamic digital geological map of Europe. It was a project of the European Commission (eContentPlus programme), carried out from 2008 to 2010 by 30 cooperating organisations. Of these, 20 were European Geological Surveys. The result was the discoverability and accessibility of geological maps from 26 European countries at a scale of 1:1 million. Despite the fact that this dataset includes numerous geometrical and semantic offsets at state borders, this project significantly contributed to the progress of INSPIRE in developing a harmonised data model based on Geoscience Markup Language for 1:1 million geological map data and provided this data through Open Geoscience Consortium-compliant web services. The data was further developed after the end of the project and is available on EGDI.

Despite these major steps forward, more data are needed: for many applied tasks – even at the regional level of spatial planning issues – geological basic data are needed on a much more detailed scale than 1:1 million. Significant progress has been made in this regard within GeoERA, in particular through the projects:

- GeoConnect3d - multidimensional data model and pilot regions datasets;
- HIKE - hierarchic classification of faults and fault database of 14 European countries; and

- 3DGeo-EU - technical innovation in harmonised 3D-modelling and visualisation, including pilot studies.

Further efforts are also underway through the continued work of the EGS Geological Mapping and Modelling Expert Group. To initiate effective cross-border harmonisation beyond pilot studies and to assist in search and identification of existing sources of information, an inventory will be made of geological maps, map data and multiscale 2D and 3D models from all European geological surveys. The analysed information will be processed in the form of metadata in the EGDI Metadata Catalogue to make the relevant data conform to FAIR standards, to support current and future European projects. The involvement of all geological surveys is crucial, as metadata should be complete, constantly maintained, and kept up to date. To achieve a higher level of harmonisation and interoperability of national geological datasets at the European level, it is essential to improve and further develop scientific vocabularies and nomenclatures. Results will be publicly available in the EGDI knowledge base by linked-data technology. Moreover, existing data models will be further developed in their ability to take up and deliver multiscale geological data and information requested. The aim is to realise these goals over the next five years through a Coordination and Support Action aimed at establishing a sustainable Geological Service for Europe.

Geology for policy

As our cities and living environments change ever faster with the wide-ranging impacts of climate change, securing and providing sound geological data, information, and knowledge becomes crucial for resilient decision making. What areas should be reserved for future energy storage? How do we prioritise competing land uses? What are the risks to our multi-use coastal zones? How do we manage water resources sustainably and on a European scale? Many people will not associate these and other questions with geology. In fact, while public understanding of geology is generally scant (e.g. Stewart and Lewis, 2013) – often limited to ‘dinosaurs and disasters’ – geology covers a very broad spectrum of fields. This geological diversity is reflected in the EGS Expert Groups, established to directly inform EU strategy and policy: Mineral Resources, Water Resources, Geochemistry, Urban Geology, Earth Observation and Geohazards, Geological Mapping and Modelling, Spatial

Data, GeoEnergy, Marine Geology, Geoheritage. The breadth of social issues that the work of these Expert Groups applies to is vast: city planning, soil health and agriculture, competing land uses, biodiversity, drinking water and healthy waterways, management of coastal zones, mineral potential and mining, green energy production and storage, and placement of wind farms, to name some. Furthermore, the data produced by the Expert Groups is directly relevant to EU strategy and policy in a broad range of areas, and to supporting the EU Sustainable Development Goals. The data are also supported by the cross-border knowledge-sharing between Geological Survey Organisations and our partners.

The flagship EGS Geochemical Atlas of Europe, for instance, stemmed from the original EGS Geochemical Working Group, which had been established to develop a geochemical baseline to support definitions of contaminant limits for soils. This work directly contributed to the future EU Soil Protection Directive (European Commission, 2002; 2006). Similarly, knowledge of the baseline chemistry of water and soils is essential to carry out work within the scope of the Water Framework Directive, the Mine Waste Directive, or the REACH Regulation (Registration, Evaluation, Authorisation and Restriction of Chemicals), among others. As another example, our Mineral Resources Expert Group plays a key role in compiling and delivering information and knowledge of our existing mineral resources, and also the potential for new discoveries and reworking of secondary sources. This is crucial baseline information for the supply of CRM for the green energy transition and to achieve the goals of the European Green Deal. Without a sound knowledge of our own raw materials vulnerabilities, it is difficult to strategically plan to secure our supply chains and prioritise the required international partnerships needed. Even in environments as complex as our cities, our experts are in the unique position of contributing to bridging knowledge gaps, working with city planners to assess land use conflicts and contribute the subsurface data, information, and knowledge required to make planning decisions in the face of the significant impacts of climate change on our built environment. These efforts, channelled through our new Urban Geology Expert Group, directly contribute toward achieving UN SDG 11, making cities inclusive, safe, resilient and sustainable (Sustainable Cities and Communities) and the New Urban Agenda (United Nations, 2017), to support the sustainable development of

urban environments. These are just three of the many examples provided here. All of our Expert Groups aim to generate geological data, information, and knowledge, and to deliver advice directly relevant to supporting EU policy and strategy.

Decision-making on the European scale requires that the supporting geological data be harmonised on a pan-European scale. Geology, water, coastlines, geohazards, even – in some cases – cities do not stop at borders. In this regard, the EGS collaborative network is crucial, as only geological survey organisations, acting collectively, have access to the data, information, and knowledge required to generate and maintain pan-European harmonised datasets. While the European geological survey organisations have been collecting geological data for up to more than a century, they have also been working for decades to harmonise these datasets on a European scale, in line with the INSPIRE Directive (2007) and FAIR data principles (Wilkinson *et al.*, 2016). In fact, the data infrastructure required to support harmonised pan-European geological data forms the core of EuroGeoSurveys’ vision of a future Geological Service for Europe – the European Geological Data Infrastructure. While EGDI was initially envisaged as an essential starting point for delivery of harmonised data, its development has made clear its fundamental role. This EGDI infrastructure, the centrepiece of efforts by our Spatial Information Expert Group, holds a wealth of pan-European data – on groundwater, mineral resources, geological maps, hazards, geochemistry, and much more, the results of multiple European projects and the data archives of the national surveys. The EGDI is now envisaged as the future repository and portal for new data, building on the existing datasets. And building those datasets is a key issue. While integration and maintenance of the datasets is vital to making the best use of baseline data, geological data are not static. A snapshot of data in time will not deliver the support necessary to continue to make resilient decisions. To deliver the necessary baseline geological data to underpin EU strategy and policy also requires the continued collection of high quality, up-to-date data to feed these datasets – groundwater levels, ground instability measurements, geological mapping at the scale required to understand geoenery storage, earth observation data to inform on coastal degradation, mining activities, and much more. Through a future Geological Service for Europe – the natural successor of EGS’ efforts to integrate data

and expertise on a European scale – the Geological Surveys of Europe will expand their ability to provide ongoing support for resilient decision making on the basis of expert knowledge and sound geological data.

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References

- Admiraal, H., Cornaro, A. 2016. Why underground space should be included in urban planning policy - and how this will enhance an urban underground future. *Tunnelling and Underground Space Technology*, 55: 214–220; doi.org/10.1016/j.tust.2015.11.013
- Archer, N.A.L., Bell, R.A., Butcher, A.S., Bricker, S.H. 2020. Infiltration efficiency and subsurface water processes of a sustainable drainage system and consequences to flood management. *Journal of Flood Risk Management*, 13 (3): e12629. <https://doi.org/10.1111/jfr3.12629>
- Bazilian, M., Rogner, H., Howells, M., Hermann, S., Arent, D., Gielen, D., Steduto, P., Mueller, A., Komor, P., Tol, R. S. J., & Yumkella, K. K. 2011. Considering the energy, water and food nexus: Towards an integrated modelling approach. *Energy Policy*, 39(12): 7896–7906. <https://doi.org/10.1016/j.enpol.2011.09.039>
- Bertrand, G., Cassard, D., Arvanitidis, N., Stanley, G. 2016. Map of Critical Raw Material Deposits in Europe, *Energy Procedia*, 97: 44–50. <https://doi.org/10.1016/j.egypro.2016.10.016>
- BiTC. 2018. Water Resilient Cities, A business case for Greater Manchester. *Business in the Community Report*. London. <https://naturalcourse.co.uk/uploads/2018/10/water-resilient-cities-report-july-2018.pdf> [Accessed 17.01.2022].
- Bricker, S.H. 2021. Foundations for a future net zero city? *British Geological Survey blog*. www.bgs.ac.uk/news/foundations-for-a-future-net-zero-city/ [Accessed 17.01.2022]
- Broers, H. P., Sültenfuß, J., Aeschbach, W., Kersting, A., Menkovich, A., de Weert, J., Castelijns, J. 2021. Paleoclimate signals and groundwater age distributions from 39 public water works in the Netherlands; Insights From noble gases and carbon, hydrogen and oxygen isotope tracers. *Water Resources Research*, 57: e2020WR029058. <https://doi.org/10.1029/2020WR029058>
- Commission of the European Communities, 2008. COM(2008) 699 final, COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL: The raw materials initiative — meeting our critical needs for growth and jobs in Europe, 14pp.
- Crozier, M. J., 2005. Multiple occurrence regional landslide events in New Zealand: Hazard management issues. *Landslides*, 2: 247–256.
- de Oliveira, D.P.S., Filipe, A., Gonçalves, P., Santos, S., Albardeiro, L. 2021. Critical Raw Materials Deposits Map of Mainland Portugal: New Mineral Intelligence in Cartographic Form, *The Cartographic Journal*, <https://doi.org/10.1080/00087041.2021.1977882>.
- de Oliveira, D.P.S., Ferreira, M.J., Sadeghi, M., Arvanitidis, N., Bertrand, G., Decrée, S., Gautneb, H., Gloaguen, E., Törmänn, T., Reginiussen, H., Sievers, H., Quental, L., Wittenberg, A. 2020a. "FRAME's (Forecasting and Assessing Europe's Strategic Raw Materials Needs) innovative research in mineral raw materials on the eve of the EU's "Green Deal" GeoUtrecht2020 Utrecht, The Netherlands: 24-26th August 2020, Abstracts Submission 119.
- de Oliveira, D.P.S., Ferreira, M.J., Sadeghi, M., Arvanitidis, N., Decrée, S., Gautneb, H., Gloaguen, E., Törmänn, T., Reginiussen, H., Sievers, H., Quental, L., Wittenberg, A. 2020b. "FRAME's (Forecasting and Assessing Europe's Strategic Raw Materials Needs) contribution to the "European Green Deal". EGU General Assembly 2020, 4-8 May 2020, EGU2020-5950. <https://doi.org/10.5194/egusphere-egu2020-5950>.
- de Roo, A., Trichakis, I., Bisselink, B., Gelati, E., Pistocchi, A., Gawlik, B. 2021. The Water-Energy-Food-Ecosystem Nexus in the Mediterranean: Current Issues and Future Challenges. *Frontiers in Climate*, 3. <https://doi.org/10.3389/fclim.2021.782553>.
- Dearden, R.A., Marchant, A., Royse, K. 2013. Development of a suitability map for infiltration sustainable drainage systems (SuDS). *Environmental Earth Sciences*, 70 (6): 2587–2602. doi.org/10.1007/s12665-013-2301-7.
- Demetriades, A., Reimann, C., Birke, M., Salminen, R., De Vos, W., Tarvainen, T., EuroGeoSurveys Geochemistry Expert Group, E.G.E.G. 2010. Geochemical atlases of Europe produced by the EuroGeoSurveys geochemistry expert group: state of progress and potential uses. *Bulletin of the Geological Society of Greece*, 43(5): 2350–2360. doi:<https://doi.org/10.12681/bgsg.11635>.

- De Vos W., Tarvainen T. (Eds), Salminen R., Reeder S., De Vivo B., Demetriades A., Pirc, S., Batista M.J., Marsina K., Ottesen R.T., O'Connor P.J., Bidovec M., Lima A., Siewers U., Smith B., Taylor H., Shaw R., Salpeteur I., Gregorauskiene V., Halamic J., Slaninka I., Lax K., Gravesen P., Birke M., Breward N., Ander E.L., Jordan G., Duris M., Klein P., Locutura J., Bellan A., Pasieczna A., Lis J., Mazreku A., Gilucis A., Heitzmann P., Klaver G., Petersell V. 2006. Geochemical Atlas of Europe. Part 2 - *Interpretation of Geochemical Maps, Additional Tables, Figures, Maps, and Related Publications*. Geological Survey of Finland, Espoo, 692 pp.
- Dick, G., Eriksson, I., De Beer, J., Bonsor, H., Van der Lugt, P. 2017. Planning the city of tomorrow: Bridging the gap between urban planners and subsurface specialists. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, 108(2-3): 327–335. doi:10.1017/S1755691018000361
- EGDI. 2022. Map viewer and data access point for all GeoERA projects. <https://geoera.eu/projects/gip-p/overall-geoera-map/> [Accessed 01-02-2022].
- European Commission. 2002. *Communication from the Commission to the council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Thematic Strategy for Soil Protection*; Brussels, 22.9.2006 COM(2006)231 final, p. 7. Available at: <https://eur-lex.europa.eu/legalcontent/EN/TXT/PDF/?uri=CELEX:52006DC0231&from=EN>.
- European Commission. 2006. *Directive of the European Parliament and of the Council establishing a framework for the protection of soil and amending Directive 2004/35/EC COM(2006)232 final*. Brussels, Belgium, European Union. Retrieved from <https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0232:FIN:EN:PDF>.
- European Commission. 2016. EIP on Raw Materials, *Raw Materials Scoreboard*. doi:10.2873/686373
- European Commission. 2018. EIP on Raw Materials, *Raw Materials Scoreboard*. doi:10.2873/08258.
- European Commission, 2022. A European Green Deal – striving to be the first climate-neutral continent. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en, [Accessed 02-02-2022].
- European Environment Agency. 2021. Europe's changing climate hazards - an index-based interactive EEA report. Published 17 Nov 2021, Last modified 30 Nov 2021. <https://www.eea.europa.eu/publications/europes-changing-climate-hazards-1>
- European Environment Agency. 2022. <https://www.eea.europa.eu/data-and-maps/data/wise-eionet-spatial-3> - [Accessed 04-02-2022].
- GeoERA. 2022. Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe. <https://geoera.eu/>, [Accessed 21.01.2022].
- Gleeson, T., Wang-Erlandsson, L., Porkka, M., Zipper, S.C., Jaramillo, F., Gerten, D., Fetzer, I., Cornell, S.E., Piemontese, L., Gordon, L.J., Rockström, J., Oki, T., Sivapalan, M., Wada, Y., Brauman, K.A., Flörke, M., Bierkens, M.F.P., Lehner, B., Keys, P., Kumm, M., Wagener, T., Dadson, S., Troy, T.J., Steffen, W., Falkenmark, M., Famiglietti, J.S. 2020. Illuminating water cycle modifications and Earth system resilience in the Anthropocene. *Water Resources Research*, 56: 1–24. <https://doi.org/10.1029/2019WR024957>
- Guinan, J., McKeon, C., O'Keeffe, E., Monteys, X., Sacchetti, F., Coughlan, M., Nic Aonghusa, C. 2020. INFOMAR data supports offshore energy development and marine spatial planning in the Irish offshore via the EMODnet Geology portal. *Quarterly Journal of Engineering Geology and Hydrogeology*, 54, art. no. qjgh2020-033. <https://doi.org/10.1144/qjgh2020-033>
- Herrera, G., Mateos, R. M., García-Davalillo, J. C., Grandjean, G., Poyiadji, E., Maftai, R., Filipciuc, T.C., Jemec Aulic M., Jež, J., Podolszki, L., Trigila, A., Ladanza, C., Raetzo, H., Kociu A., Przyłucka, M., Kułak M., Sheehy, M., Pellicer, X.M., McKeown, C., Ryan, G., Kopačková, V., Frei, M., Kuhn, D., Hermanns, R.L., Koulermou, N., Smith, C.A., Engdahl, M., Buxó, P., Gonzalez, M., Dashwood, C., Reeves, H., Cigna F., Liščák, P., Paudiš, P., Mikulénas V., Demir V., Raha, M., Quental L., Sandić C., Fusi B. Jensen O. A. 2017. Landslide databases in the Geological Surveys of Europe. *Landslides*, 15: 359–379.
- Hinsby, K., Auken, E., Essink, G.H.P.O., de Louw, P., Siemon, B., Sonnenborg, T.O., Wiederholdt, A., Guadagnini, A., Carrera, J., (eds.) 2011. Assessing the impact of climate change for adaptive water management in coastal regions. *Hydrology and Earth System Sciences*, special issue 149.
- Hinsby, K., Condeso de Melo, M.T., Dahl, M. 2008. European case studies supporting the derivation of natural background levels and groundwater threshold values for the protection of dependent ecosystems and human health. *Science of the Total Environment*, 401:1–20. <https://doi.org/10.1016/j.scitotenv.2008.03.018>

- Hinsby, K., Edmunds, W.M., Loosli, H.H., Manzano, M., Condesso De Melo, M.T., Barbecot, F. 2001. The modern water interface: Recognition, protection and development - Advance of modern waters in European aquifer systems. *Geological Society, London, Special Publication*, 189: 271–288.
- Hinsby, K., Markager, S., Kronvang, B., Windolf, J., Sonnenborg, T.O., Thorling, L. 2012. Threshold values and management options for nutrients in a catchment of a temperate estuary with poor ecological status. *Hydrology and Earth System Sciences*, 16, 2663–2683, <https://doi.org/10.5194/hess-16-2663-2012>
- Hughes, A.G., Vounaki, T., Peach, D.W., Ireson, A.M., Jackson, C.R., Butler, A.P., Bloomfield, J.P., Finch, J., Wheeler, H.S. 2011. Flood risk from groundwater: Examples from a Chalk catchment in southern England. *Journal of Flood Risk Management*, 4(3): 143–155. <https://doi.org/10.1111/j.1753-318X.2011.01095.x>
- Kaskela, A.M., Kotilainen, A.T., Alanen, U., Cooper, R., Green, S., Guinan, J., van Heteren, S., Kihlman, S., Van Lancker, V., Stevenson, A., the EMODnet Consortium. 2019. Picking up the pieces—Harmonising and collating seabed substrate data for European maritime areas. *Geosciences*, 9(2), 84. <https://doi.org/10.3390/geosciences9020084>
- Lade, S. J., Steffen, W., de Vries, W., Carpenter, S. R., Donges, J. F., Gerten, D., Hoff, H., Newbold, T., Richardson, K., Rockström, J. 2020. Human impacts on planetary boundaries amplified by Earth system interactions. *Nature Sustainability*, 3(2): 119–128. <https://doi.org/10.1038/s41893-019-0454-4>.
- Lentini, A., Meddi, E., Galve, J.P., La Vigna, F., Papiccio, C., and Oursaire, A. 2021. Identifying areas suitable for Sustainable Drainage Systems and Aquifer Storage and Recovery to mitigate stormwater flooding phenomena in Rome (Italy). Conference Proceedings. Conference of the Italian Geological Society. SGI CONGRESS 2021.
- Lewis, S.L., Maslin, M.A. 2015. Defining the Anthropocene. *Nature*, 519 (7542): 171–180. <https://doi.org/10.1038/nature14258>
- Martín Míguez, B., Novellino, A., Vinci, M., Claus, S., Calewaert, J.B., Vallius, H., Schmitt, T., Pititto, A., Giorgetti, A., Askew, N., Iona, S., Schaap, D., Pinardi, N., Harpham, Q., Kater, B.J., Populus, J., She, J., Palazov, A.V., McMeel, O., Oset, P., Lear, D., Manzella, G.M.R., Gorringer, P., Simoncelli, S., Larkin, K., Holdsworth, N., Arvanitidis, C.D., Molina, J.M.E., Chaves Montero, M., Herman, P.M.J., Hernandez, F. 2019. The European Marine Observation and Data Network (EMODnet): Visions and Roles of the Gateway to Marine Data in Europe. *Frontiers in Marine Science*, 6. <https://www.frontiersin.org/article/10.3389/fmars.2019.00313>
- Martinsen, G., Bessiere, H., Caballero, Y., Koch, J., Collados-Lara, A.J., Mansour, M., Sallasmaa, O., Pulido Velázquez, D., Williams, N.J., Zaanboordijk, W.J., Stisen, S. 2022. Developing a pan-European high-resolution groundwater recharge mapping – combining satellite data and national survey data using machine learning. *Science of the Total Environment*: 822, 153464. <https://doi.org/10.1016/j.scitotenv.2022.153464>
- Mateos, R.M., García-Moreno, I., Azañón, J.M. 2012. Freeze-thaw cycles and rainfall as triggering factors of mass movements in a warm Mediterranean region: the case of the Tramuntana Range Majorca, Spain. *Landslides*, 9: 417–432.
- Mateos, R.M., López-Vinielles, J., Poyiadji E., Tsagkas, D., Sheehy, M., Hadjicharalambous, K., Liscák, P., Podolski, L., Laskowicz, I., Ladanza, C., Gauert, C., Todorović, S., Jemec, Auflič, M., Maftai, R., Hermanns, R.L., Kociu, A., Sandić, C., Mauter, R., Sarro, R., Béjar, M., Herrera, G. 2020. Integration of landslide hazard into urban planning across Europe, *Landscape and Urban Planning*, 196: 103740, , <https://doi.org/10.1016/j.landurbplan.2019.103740>.
- Moses, C.A., Vallius, H. 2020. Mapping the Geology and Topography of the European Seas (European Marine Observation and Data Network, EMODnet). *Quarterly Journal of Engineering Geology and Hydrogeology*, 54, qjehg2020-131, <https://doi.org/10.1144/qjehg2020-131>
- Quevauviller, P. 2022. A Review on Connecting Research, Policies and Networking in the Area of Climate-Related Extreme Events in the EU with Highlights of French Case Studies. *Atmosphere* 2022, 13, 117. <https://doi.org/10.3390/>.
- Reimann, C., Caritat de, P. 2017. Establishing geochemical background variation and threshold values for 59 elements in Australian surface soil. *Science of the Total Environment*, 578: 633–648.
- Reimann, C., Birke, M., Demetriades, A., Filzmoser, P., O'Connor, P. (eds) 2014a. Chemistry of Europe's agricultural soils (A): Methodology and interpretation of the GEMAS dataset. *Geologisches Jahrbuch*, Schweizerbarth, Stuttgart.
- Reimann, C., Birke, M., Demetriades, A., Filzmoser, P., O'Connor, P. (eds) 2014b. Chemistry of Europe's agricultural soils (B): General background information and analysis of the GEMAS dataset. *Geologisches Jahrbuch*, Schweizerbarth, Stuttgart.

- Reimann, C., Fabian, K., Birke, M., Filzmoser, P., Demetriades, A., Négrel, Ph., Oorts, K., Matschullat, J., Caritat, de P. 2018. GEMAS: Establishing geochemical background and threshold for 53 chemical elements in European agricultural soil. *Applied Geochemistry*, 88: 302–318.
- Ryabchuk, D., Sergeev, A., Burnashev, E., Khorikov, V., Neevin, I., Kovaleva, O., Budanov, L., Zhamoida, V., Danchenkov, A. 2020. Coastal processes in the Russian Baltic (eastern Gulf of Finland and Kaliningrad area). *Quarterly Journal of Engineering Geology and Hydrogeology*, 54, qjagh2020-036, <https://doi.org/10.1144/qjagh2020-036>.
- Salminen R. (Ed.), Batista, M.J., Bidovec, M., Demetriades, A., De Vivo, B., De Vos, W., Duris, M., Gilucis, A., Gregorauskiene, V., Halamic, J., Heitzmann, P., Lima, A., Jordan, G., Klaver, G., Klein, P., Lis, J., Locutura, J., Marsina, K., Mazreku, A., O'Connor, P.J., Olsson, S.Å., Ottesen, R.T., Petersell, V., Plant, J.A., Reeder, S., Salpeteur, I., Sandström, H., Siewers, U., Steenfelt, A. Tarvainen, T. 2005. *FOREGS Geochemical Atlas of Europe, Part 1: Background Information, Methodology and Maps*. Geological Survey of Finland, Espoo.
- Smith, D.B., Smith, S.M., Horton, J.D. 2013. History and evaluation of national-scale geochemical data sets for the United States. *Geoscience Frontiers*, 4(2): 167–183.
- Steffen, W., Richardson, K., Rockström, J., Cornellino, S.E., Fetzer, I., Bennett, E.M., Biggs, R., Carpenter, S.R., De Vries, W., De Wit, C.A., Folke, C., Gerten, D., Heinke, J., Mace, G.M., Persson, L.M., Ramanathan, V., Rayers, B., Sörlin, S. 2015. Planetary boundaries: Guiding human development on a changing planet. *Science*, 347 (6223), doi.org/10.1126/science.1259855.
- Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D., Summerhayes, C.P., Barnosky, A.D., Cornell, S.E., Crucifix, M., Donges, J.F., Fetzer, I., Lade, S.J., Scheffer, M., Winkelmann, R., Schellnhuber, H.J. 2018. Trajectories of the Earth System in the Anthropocene. *Proceedings of the National Academy of Sciences, U.S.A.*, 115: 8252–8259. <https://doi.org/10.1073/pnas.1810141115>.
- Stewart, I.S., Lewis D. 2013. Communicating contested geoscience to the public: Moving from 'matters of fact' to 'matters of concern'. *Earth-Science Reviews*, 174, 122–133. <https://doi.org/10.1016/j.earscirev.2017.09.003>.
- Stisen, S., Soltani, M., Mendiguren, G., Langkilde, H., Garcia, M., Koch, J. 2021. Spatial Patterns in Actual Evapotranspiration Climatologies for Europe. *Remote Sensing*, 13: 2410. <https://doi.org/10.3390/rs13122410>
- SWD(2017)128, 2017. *Report on the Blue Growth Strategy Towards more sustainable growth and jobs in the blue economy*, Commission Staff Working Document..
- Terrinha, P., Medialdea, T., Batista, L., Somoza, L., Magalhães, V., Javier González, F., Noiva, J., Lobato, A., Rosa, M., Marino, E., Brito, P., Neres, M., Ribeiro, C. 2020. Integrated thematic geological mapping of the Atlantic Margin of Iberia. *Geological Society, London, Special Publications*, 505. <https://doi.org/10.1144/SP505-2019-90>
- UNECE. 2021a. Draft UNFC supplemental specifications for groundwater. <https://unece.org/sed/documents/2021/02/working-documents/draft-unfc-supplemental-specifications-groundwater> [Accessed 02-02-2022].
- UNECE. 2021b. United Nations Resource Management System - An Overview of Concepts, Objectives and Requirements. UNECE report, pp. 64, <https://shop.un.org/fr/node/92465> [Accessed 02-02-2022].
- United Nations. 2015. Sendai Framework for Disaster Risk Reduction 2015–2030. Geneva: United Nations 32 pages, (https://www.preventionweb.net/files/43291_sendaiframeworkfordrren.pdf).
- United Nations. 2017. New Urban Agenda, Habitat III, Quito, Ecuador. A/RES/71/256. United Nations. 2022. United Nations Sustainable Development Goals. <https://sdgs.un.org/goals> [Accessed 02-02-2022].
- Vallius, H.T.V., Kotilainen, A.T., Asch, K.C., Fiorentino, A., Judge, M., Stewart, H.A., Pjetursson, B. 2020. Discovering Europe's seabed geology: the EMODnet concept of uniform collection and harmonization of marine data. *Geological Society, London, Special Publications*, 505, <https://doi.org/10.1144/SP505-2019-208>.
- van der Meulen, M., Campbell, S.D.G., Lawrence, D.J., Lois González, R.C., van Campenhout, I. 2016. Out of Sight, Out of Mind? Considering the subsurface in urban planning - State of the art. COST Sub-Urban WG1 Report. TU1206-WG1-001.
- Venvik, G., Bang-Kittilsen, A. and Boogaard, F.C. 2020. Risk assessment for areas prone to flooding and subsidence: a case study from Bergen, Western Norway. *Hydrology Research*, 51 (2): 322–338. <https://doi.org/10.2166/nh.2019.030>.

Volchko, Y., Norrman, J., Ericsson, L.O., Nilsson, K.L., Markstedt, A., Oberg, M., Mossmark, F., Bobylev, N., Tengborg, P. 2020. Subsurface planning: Towards a common understanding of the subsurface as a multifunctional resource. *Land Use Policy*, 90, 104316. <https://doi.org/10.1016/j.landusepol.2019.104316>

Wang, X., Liu, X., Han, Z., Zhou, J., Xu, S., Zhang, Q., Chen, H., Bo, W., Xia, X. 2015. Concentration and distribution of mercury in drainage catchment sediment and alluvial soil of China. *Journal of Geochemical Exploration*, 154: 32–48.

Water Framework Directive. 2000/60/EC. <https://lexparency.org/eu/32000L0060/>

WEFE. 2019. Position Paper on Water, Energy, Food, and Ecosystem (WEFE) Nexus and Sustainable development Goals (SDGs). Editors: C. Carmona-Moreno, C. Dondeynaz, M. Biedler, EUR 29509 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-79-98276-7, [doi:10.2760/5295](https://doi.org/10.2760/5295), [JRC114177](https://doi.org/10.2760/5295).

Werner, A.D., Bakker, M., Post, V.E.A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., Simmons, C.T., Barry, D.A. 2013. Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources*, 51: 3–26. <https://doi.org/10.1016/j.advwatres.2012.03.004>.

Wilkinson, M., Dumontier, M., Aalbersberg, I. 2016. The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3 (160018), [doi: 10.1038/sdata.2016.18](https://doi.org/10.1038/sdata.2016.18).

Wittenberg, A., de Oliveira, D.P.S., Jørgensen, L.F., Gonzalez, F.J., Sievers, H., Quental, L., Pereira, A., Heldal, T., Whitehead, D. 2020a. Raw materials -you can't do well without them. GeoUtrecht2020 Utrecht, The Netherlands: 24–26th August 2020, Abstract 140.

Wittenberg, A., de Oliveira, D.P.S., Gonzalez Sanz, F., Jørgensen, L.F., Whitehead, D. and Heldal, T. 2020b. Mineral Resources – Crucial components of a vital and wealthy society. EGU General Assembly 2020, 4–8 May 2020, EGU2020-7947, <https://doi.org/10.5194/egusphere-egu2020-7947>.



How to ensure better consideration and mitigation of the shrinkage–swelling risk of clays?

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For several years, climate change in Luxembourg has increasingly resulted, among other things, in precipitation deficits, which causes damage linked to the phenomenon of shrinkage–swelling of clays, affecting both buildings and infrastructures. The south of Luxembourg, with its predominantly marly and clayey Triassic and Jurassic rocks, is particularly at risk. While the usual stabilisation methods are often used, such as underpinning or injecting under the foundations, they have several drawbacks. As an alternative, innovative rainwater reinjection methods have been tested by our office, with encouraging results, and could help to prevent the occurrence of damage to structures. At the same time, the establishment of a hazard map and the development of technical regulations specifying the parameters to be determined and the tests to be carried out would allow better management of the risk by all stakeholders, as well as the limitation of related costs.

Depuis plusieurs années, le changement climatique au Luxembourg se traduit de plus en plus, entre autres, par des déficits de précipitations, ce qui provoque des dommages liés au phénomène de retrait-gonflement des argiles, affectant aussi bien les bâtiments que les infrastructures. Le sud du Luxembourg, avec ses roches triassiques et jurassiques à prédominance marneuse et argileuse, est particulièrement menacé. Alors que les méthodes de stabilisation habituelles soient souvent utilisées, telles que le sous-appui ou l'injection sous fondations, elles présentent plusieurs inconvénients. Dès lors, des méthodes alternatives innovantes de réinjection des eaux pluviales ont été testées par notre cabinet. Ces méthodes ont montré des résultats encourageants et pourraient contribuer à prévenir des dégradations sur les ouvrages. Parallèlement, l'établissement d'une cartographie des aléas et l'élaboration d'une réglementation technique précisant les paramètres à déterminer et les essais à réaliser permettraient une meilleure gestion du risque par l'ensemble des acteurs, ainsi que la limitation des coûts associés.

Por muchos años, el cambio climático en Luxemburgo ha dado como resultado entre otras cosas, a un déficit de precipitaciones, causando daños relacionados con fenómenos de contracción-dilatación de arcillas, que han afectado tanto a edificios como a infraestructura. La parte sur de Luxemburgo, que está formada predominantemente por rocas margosas y arcillosas del Triásico y Jurásico, es una zona de riesgo. Aunque se utilizan los métodos tradicionales de estabilización, como reforzamiento o inyección de las fundaciones, estos presentan ciertos inconvenientes. Como alternativa, nuestro grupo ha probado métodos innovadores, utilizando reinyección de agua de lluvia, con resultados alentadores que podrían prevenir la ocurrencia de daños a estructuras. Al mismo tiempo, la creación de un mapa de riesgo y la elaboración de especificaciones técnicas, indicando los parámetros a considerar y las pruebas a realizar, permitiría un mejor manejo del riesgo para todas las partes involucradas, además de la limitación de los costos involucrados.

Introduction

For several years, climate change in Luxembourg has increasingly resulted, among other things, in lower levels of precipitation than usual, which causes the appearance of damage linked to the phenomenon of shrinkage–swelling of clays, affecting both buildings and infrastructures. To illustrate this rainfall deficit, Figure 1 shows the water balance measured in Oberkorn and Remich cities, respectively located in the southwest and southeast of Luxembourg. The water balance represents the remaining water quantities after the evapotranspiration, the streamflow, and the

variation of water storage. The data shows that the water balance has been decreasing since 2004, which demonstrate a drying trend for the territory of Luxembourg.

Unlike in other countries, the natural hazard of shrinkage–swelling of clays, related to soil moisture, is not recognised by insurance companies. Moreover, our expe-

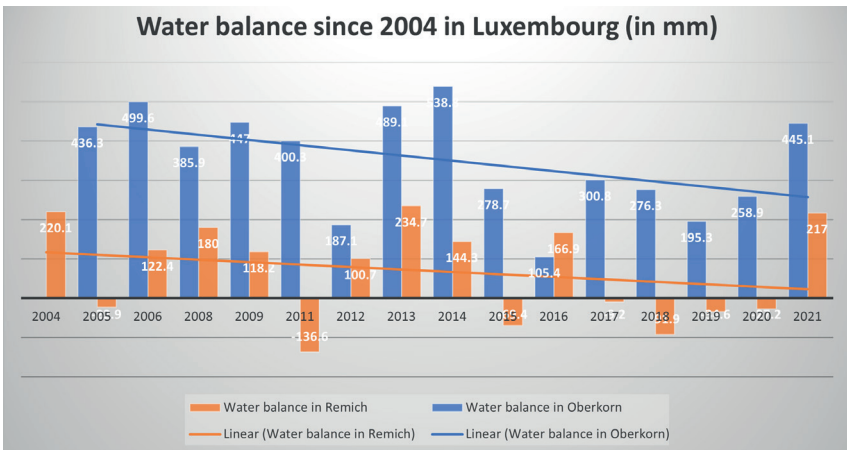


Figure 1: Water balance in the cities of Oberkorn and Remich (Luxembourg Agriculture Ministry, 2021).

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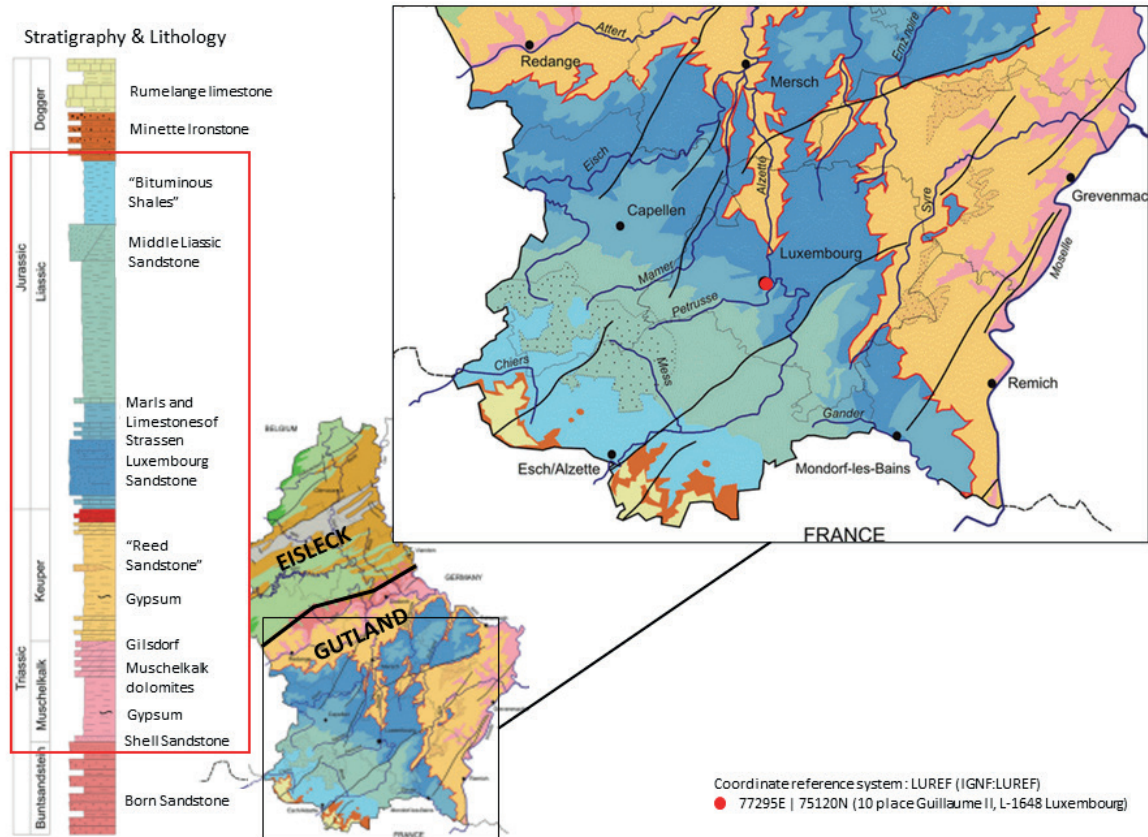


Figure 2: Geological map of the Grand Duchy of Luxembourg (GSL, 2009).

rience in Luxembourg and in the south of Belgium has demonstrated that this natural hazard is often unknown or misunderstood. For existing structures, actions dealing with it are limited and consist in intervening after damage has occurred, but it is possible to plan ahead for new construction projects.

Some countries, like France, have appropriate legislation and risk maps, which is not the case in other countries like Belgium or Luxembourg. The zones of foreseeable geological risks are not yet defined, and if the client does not surround himself with specialists aware of this risk, it will almost inevitably be forgotten, with the significant consequences that this could sometimes have. However, the phenomenon of the shrinkage–swelling of clays is one of the most widespread geological risks with consequences accentuated by the climate change, and which directly or indirectly affects a very large number of people. Indeed, as this phenomenon is linked to the humidity of clay soils, the occurrence and intensity of this phenomenon will probably continue to increase in the future. Therefore, it is absolutely necessary that awareness of the existence of this risk is raised and that it be taken into account in risk management from the design phase of the project.

In this paper, we will focus in more detail on Luxembourg, where a large part of the territory is made up of clay or clayey rocks. After a brief description of the geological situation and the characteristics of clay, we give an overview of the risks associated with its behaviour that are increasingly encountered because of climate change, discuss the classic methods of remediation and then explain an innovative method tested on a full-size site. We will thus show the results obtained in the context of remediation, keeping in mind that this technique can also be used to prevent risks and not only to remediate them.

All these considerations will allow us to draw several conclusions on the methods and means that could be implemented to promote awareness and thus contribute to reducing the risk. Indeed, too often we intervene only after damage is observed, when it would be simpler and less expensive to prevent the risk rather than to remedy it.

Geological background

Geology of Luxembourg

Luxembourg is divided in two geological regions, with different landscapes and bedrock. These two regions reflect the geo-

logical history of the Grand Duchy.

In the north, the Eisleck region is characterised by deep valleys incised in Devonian rocks (predating the Pragian and Emsian times) folded during the Hercynian orogeny. These formations represent the geological foundation of Luxembourg, and are mainly composed of schists, metasandstones, slates and quartzites (bluish-grey schists being the most common rock type). These rocks came from muddy and sandy sediments that have been consolidated over the ages. The formation thicknesses built up to several thousands of metres, and then were transformed during the Hercynian orogeny. Geological formations with schistosity are common in the Eisleck region, associated with second- or third-order folds (GSL, 2009).

From the Lower Triassic onwards (Buntsandstein), marine transgressions covered the eroded and folded Devonian basement and successively deposited sediments. The alteration products from the continent, more precisely from the Hercynian chain, were then transported by rivers and waves to the marine environment and the finer elements were carried to the seabed, where the sedimentation of clays and carbonates took place. When these elements were brought into lagoons (Middle Triassic), the

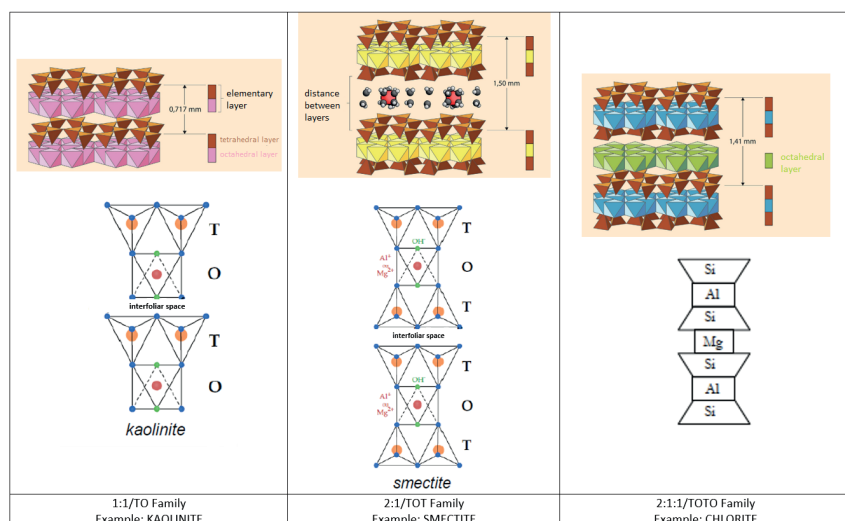


Figure 3: Mineral structure of clays (Beaufort & Pagel, n.d.; Houti, n.d.; Lafuerza, 2017).

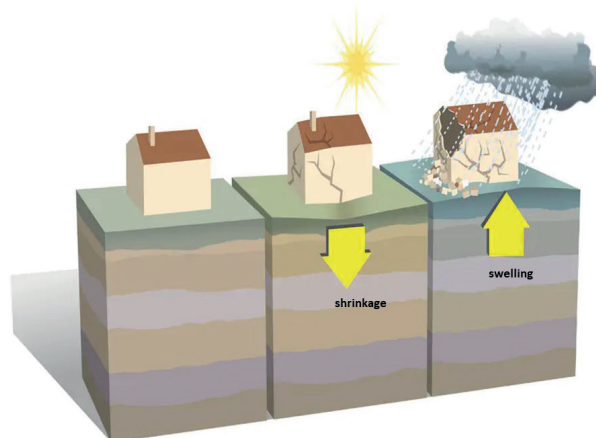


Figure 4: Graphic shrinkage and swelling (DPPR-SDPRM, 2008).

detrital input then stopped, and the tropical climate of the Triassic period allowed strong evaporation of water and clay-evaporation sedimentation. This successive sedimentation led to the rocks of the southern Luxembourg that we know today, such as marls and sandstones.

The area remained marine again until the Middle Jurassic. Subsequently, further uplift processes due to the Alpine orogeny led to the erosion of these sediments in the north of the country, leaving the Devonian rocks exposed in the Eisleck region.

In the Gutland region in the south of Luxembourg, however, some of these Triassic and Jurassic sediments have remained. Gutland is thus characterised by a succession of hard and soft consolidated sedimentary rocks, which gradually plunge towards the southern end of the country. It is in this region that in the present time marls and clays are encountered.

Definition of clay

Clay minerals are fine cohesive materials, composed of layers with water molecules between them. Clays are characterised by a grain size of less than 0.002 mm and are composed of minerals belonging to the phyllosilicate family (silicate minerals arranged in layers). Clay is a versatile mineral raw material: malleable and generally plastic when moist, it becomes cohesive, brittle, and crumbly after drying. Compound materials and clayey rocks, such as marl, also contain clay minerals and form generally soft rocks that retain the changing properties of clays in contact with water.

The sheets structuring the clays are in the nanometre range, and their size and structure depend on the minerals that compose them. There are two-layer structures, tetrahedral layers and octahedral layers; the alternation of these layers with cations forms the different minerals constituting the clay materials. Examples include kaolinite, glauconite, smectites, vermiculite and chlo-

rite (Foucault & Raoult, 2005). The layered structure of clays allows them to trap water molecules longitudinally, and thus avoid their vertical circulation. Their layered structure gives the clays strong impermeability and allows them to play an important hydrogeological role.

The different minerals can be grouped mainly into three families called 1:1 or TO, 2:1 or TOT, and 2:1:1 or TOTO, where T stands for a tetrahedral layer and O for an octahedral layer. The following table gives examples of the different family structures.

For example, the interfoliar space of smectite, like other clay minerals, depends on its hydration. Thus, the thickness of the smectite sheets is one of the most subject to variation.

Clay shrinkage–swelling phenomenon

Due to the mineral structure, clay materials are predisposed to the phenomenon of shrinkage and swelling. Clay materials exhibit different behaviour depending on their water content. Thus, a wet clay soil becomes sticky and plastic while the same soil in a dry state becomes brittle or even powdery. This change in texture is also accompanied by a variation in volume: wet clay soil tends to swell whereas it will tend to settle when it dries out (shrinkage phenomenon following the reduction in volume). The shrinkage cracks (“desiccation cracks”) which appear in a dry clay soil visually translate this variation in volume, which is simultaneously manifested by a vertical compaction of the soil. The intensity of the phenomenon is linked both to climatic conditions and to the minerals that compose the clays – smectite, vermiculite and montmorillonite are minerals that are very prone to the problem of shrinkage and swelling.

The swelling of clays occurs when water is absorbed, which increases the soil volume; physically this swelling results in a spreading of the clay layers. Shrinkage occurs when the clay dries out significantly, for example during a drought. Water evaporates from the clay, reducing its volume. The clay layers tighten, and the clays become hard and brittle. Shrinkage and swelling of clays is therefore a climate-dependent phenomenon.

The geological horizons likely to be impacted by the shrinkage–swelling phenomenon are cohesive formations with a high clay content such as clays or marls, these types of formation are located largely in the south of Luxembourg, in the Gutland region (Gruslin, S., 2019).

A wooded environment is also an aggra-



Figure 5: Desiccation crack inside a ventilated void of a house without a basement. The clays are totally dry on the inside, but their water content continues to vary on the outside, causing differential settlement and the appearance of cracks.



Figure 6: Cracks typical of a shrinkage–swelling phenomenon.

vating factor, as tree roots tend to draw water from the ground. In Luxembourg and other countries with a temperate climate, the zone of influence of this phenomenon varies between 1.0 and 1.5 m deep under grass cover, but can expand to 2.5 or even 4.0 m in the presence of large trees nearby. In addition, it is considered that a tree creates around it a permanent moisture deficit over a radius varying between 1 and 1.5 times its height (DPPR-SDPRM, 2008).

Typically, the structures affected by this phenomenon are individual houses, often built with foundations on continuous footings embedded shallowly in the ground, devoid of break joints and surrounded by trees or hedges. Annexes added to a main building with shallow or less substantial foundations are also generally more affected.

This phenomenon of shrinkage–swelling of clays leads to differential settlement of parts of the construction that are more protected and parts that are more exposed to moisture variations, creating structural disorders that result in particular in cracks in the walls. These cracks exhibit a cyclic behavior: they tend to close in winter and to open in summer, with an increase in the volume of the clay soil during rainy periods, and a decrease in volume and settlement periods of drought. In addition to the fact

that these shrinkage–swelling cycles ultimately weaken the structures, they also make any lasting repair work impossible. Therefore, the shrinkage–swelling issue should be dealt with before considering repair work. This work is generally expensive, which is why being able to anticipate risks and protect against them in advance would be beneficial for new construction.

The shrinkage and swelling of clays are not dangerous geological hazards in themselves, but they can cause significant damage to buildings and infrastructure. In temperate zones such as Luxembourg, the phenomenon of clay shrinkage induced by droughts causes the most damage. In the context of global warming, drought phenomena will be more frequent and more severe, which is why it is necessary to quantify this hazard and to propose sustainable construction methods adapted to this environment (IFSTTAR 2017, Guide 1).

Geotechnical investigations

In addition to a glance at the geological map and a minimum knowledge of the geological and geotechnical conditions of the terrain, several relatively simple and quick tests are sufficient to determine whether the construction soils present a risk of shrinkage–swelling. These include the Atterberg limits, tests to determine the limits of shrinkage or even tests to determine the clay content, either the blue value test or – even better – mineralogical analyses to determine the proportion and type of clay minerals, some being more at risk than others of modifying the volume in the event of a change in the moisture content. Indeed, the blue test, although it is very quick and easy to use, is limited by the fact that methylene blue is in fact preferentially adsorbed by clays of the montmorillonite type (swelling clays) and organic matter. The other clays (illites and kaolinites) are not very sensitive to blue (IFSTTAR 2017, Guide 1).

In addition to these tests, the determination of the water content makes it possible to check whether there is a difference in natural water content between the protected zone and the exposed zone or even according to the seasons. Significant variations in water content are an additional indicator for quantifying the risk.

These tests, which are easy to perform and relatively inexpensive, are often left out, either for cost reasons or for time constraints, with project owners generally wanting the project to move forward as quickly as possible. However, taking a little more time at the beginning of the

project saves money and worries for the future. For larger projects, oedometer compressibility tests also provide a good idea of the deformation behaviour of foundation soils. The development of technical rules or binding specifications requiring a minimum number of geotechnical tests to be carried out would make it possible to identify the risk and to be able to protect against it.

For structures affected by the phenomenon of shrinkage–swelling of clays, several classic remediation techniques exist. They are briefly summarised in the next section. However, these techniques have the big disadvantages of being expensive and sometimes causing relatively significant damage to the environment.

Typical mitigation techniques

To remedy the problem, it is possible to act either on the environment close to the construction, or to act on the foundations, or to act on the structure itself (IFSTTAR 2017, Guide 3).

First of all, it is necessary to control the variations of water infiltrating the soil and avoid having areas saturated with water and others not. However, this measure alone will not be sufficient. To limit variations in water content in the soil in the immediate vicinity of the foundations, the construction of a waterproof belt around the house can also be considered. This can be done by surrounding the building with a watertight system that is as wide as possible (minimum 1.5 m wide) protecting its immediate periphery from evaporation and keeping runoff water away that can infiltrate and modify subsoil water conditions. This system can be achieved by means of a concrete sidewalk or any other material with sufficient sealing or, in particular for aesthetic reasons, using a geomembrane buried under the topsoil to prevent changes in soil moisture (DPPR-SDPRM, 2008).

As far as possible, all shrubby vegetation should be kept away from the building at a distance of less than 1.5 times its height at maturity. In the event that felling is not possible, the creation of an anti-root screen can be considered. This consists in setting up a screen opposing the roots of a depth greater than the root system, with a minimum depth in all cases of 2 m, along the facades concerned. It should also be ensured that the consequences of a heat source located in the basement (boilers, etc.) are limited to prevent the ground from drying out around this heat source. If necessary, a thermal insulation device is to be provided (DPPR-SDPRM, 2008).

The most important and most suitable

measure to avoid any problem in the future is to carry out an adaptation of the foundations in order to increase their anchoring depth and to extend them deeper than the slice of the ground concerned by the variations in the moisture content. For existing foundations, this can generally be done either by a classic underpinning of the foundations, by using micropiles, or if we want to correct the settlement instead to resolve the problem, by means of expanding resin injections. Micropiles and underpinnings can be carried out without major specific engines, but only make it possible to support the existing foundations without being able to counter the deformations which have already occurred. Injections have the advantage of being able, to a certain extent, to pressurise the existing foundations, which makes it possible to correct (at least in part) the deformations but requires a specialised company. The equipment used is also compact, which is better in narrow areas.

For economic and ecological reasons, the use of innovative more eco-friendly methods requiring little equipment would be preferred. For this reason, we tested on a full-scale site the reinjection during the dry period of water captured and stored during the wet period. This makes it possible to maintain a constant water content in the clays whatever the season and thus to avoid any movement. Another advantage of this method is that it can be a method of prevention and not only of remediation.

Case study

The studied case is a single-family building affected by differential settlement in the south of Luxembourg.

General context

The analysed building is a single-family house with a plan dimension of 12×11 m,



Figure 7: Photos of the building.

with 3 floors and a basement. It is located in Esch-sur-Alzette, in rue Bessemer (Figure 7). The construction is from the 1920s and it is located at the end of a complex of terraced houses positioned along the street on the southwest side. Boulevard Prince Henry develops in a northwest-southeast direction at 15 m from the house. The semi-detached building is located on the northwest side. The land descends along the boulevard about 10 m at a distance from the site of 300 m in the southeast direction. The building is surrounded by a garden and plants and large trees are located near the cadastral limit at 5.0 m on the south side.

Geological and geotechnical context

The studied site is situated in layers from Toarcian (Upper Lias) period according to the geological map. These are composed of foliated, claystone-marlstone rocks with calcareous concretions. The covering clays resulting from the stones weathering have medium to high plasticity.

The site-specific stratigraphy was determined with a geotechnical survey (WPW Design Office, 2019). Three boreholes (BS1, BS2, BS3) and two light dynamic tests (DPL2, DPL3) were carried out (Figure 8). The light dynamic probing provides data



on the clay consistency. Taking as the 0.0 level the building's ground floor, the soil is a sandy and silty fill between -0.90 and -2.70 m. In BS2 and BS3, clays of different colors (ranging from red to gray with depth) of stiff to very stiff consistency are found up to -5.10 m. Between -5.10 m and -6.0 m the clays have a stiff consistency, then the number of blows increases until the weathered claystone is reached. As indicated in Figure 8, the number of blows is very different in BS2 and BS3. This is related to the different moisture content, with a more plastic behaviour in the BS3 borehole due to its higher moisture content. The clays between -2.60 m and -5.10 m were classified as firm. Up to the weathered claystone layer (-7.10 m), the clays are then classified as stiff. The weathered claystone was found under -6.8 m in borehole BS1.

The consistency difference can be found in the soil water content. The analysis revealed a very significant difference between the area exposed to the east at the depth between -3.90 and -6.90 m (BS3, water content of 26%) and the southwest areas (BS1, $w=14.1\%$, BS2 $w=14.5\%$). At this depth, clays in boreholes BS1 and BS2 are classified "TM" (clays with medium plasticity) and in BS3 "TA" (clays with high plasticity) following DIN 18196. The

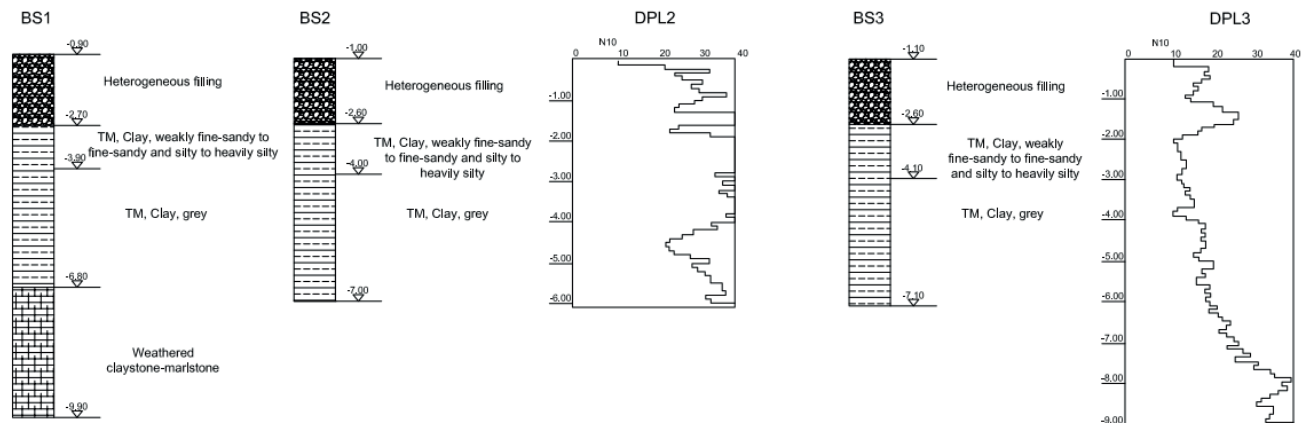


Figure 8: Site soil stratigraphy.

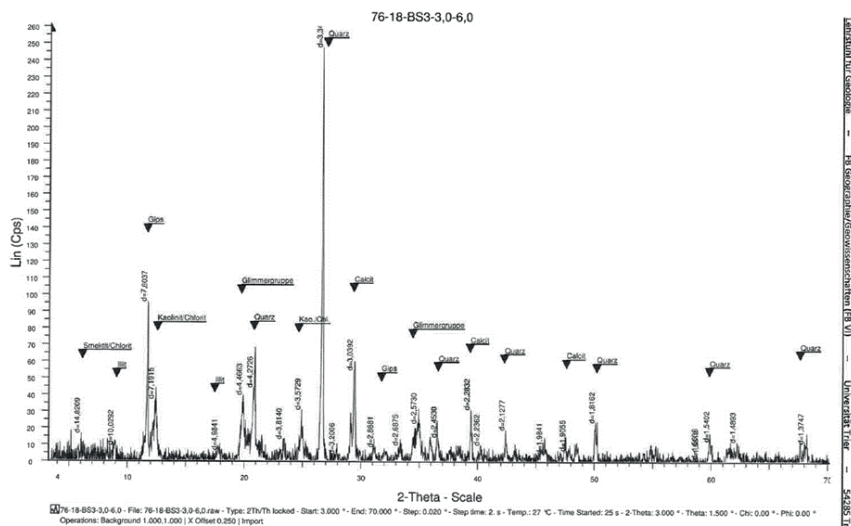


Figure 9: X-ray diffractogram on a clay sample taken from BS3 borehole (WPW Design Office, 2019).



Figure 10: Cracks in the walls and rotation of the entrance pillar.

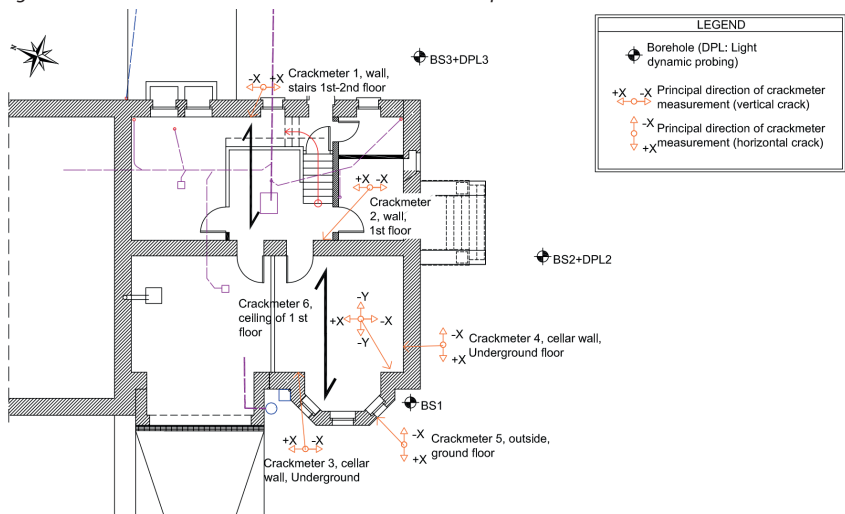


Figure 11: Plan view of the basement, direction of slab support, crackmeters and borehole position and crackmeter No. 5.

plasticity index of a clay sample from the borehole BS3 at a depth between -3.90 m and -6.80 m is 37.4 %.

A mineralogical analysis with an X-ray diffractogram was done on the claystone (BS1, depth between 6.90 and 10.0 m) and on a clay sample (BS3, between -4.10 and -7.10 m, *Figure 9*). This showed the presence, among other things, of smectite-chlorite, together with more common clay minerals like illite and kaolinite (*Figure 9*).

Building structure and events history

The building structure is made of sandstone masonry. During the works, a weak presence of bonding mortar between the stones was discovered. The perimeter walls are 50 cm wide at their base and founded on an unreinforced concrete footing 80 cm wide at -3.50 m from the ground floor. The main structural element of the floors slabs and the roof are timber beams. The ground floor is made of steel beams with concrete filling between them. The building slabs are unidirectional in the west-east direction. The foundations of the entrance stairs were at -2.40 m from the ground floor. The reinforced concrete roof of the entrance is supported by the pillars and by the perimeter wall of the house through notches.

The current owner has occupied the building during the last 20 years. During this time, microcracks were noticed but their size did not affect the aesthetics and structure of the building. From March 2018, the magnitude and diffusion of the cracks suddenly increased, especially on the south-southwest side (*Figure 10*). The crack patterns show a rotation of the building in the south-west direction. Due to its relatively low weight and a higher foundation level, the entrance suffered major rotations, as visible in *Figure 10*.

Further investigations also revealed a malfunction of the downspouts. The pipes were blocked by debris, and they were perforated by shrubs roots located along the external wall of the house. As result, the pipes could not evacuate the rainwater properly. Afterwards, the pipes were repaired, and the shrubs removed.

A monitoring system was set up in November 2019 using six crackmeters (PPW-POLYPLAN-WERKZEUGE GmbH, Rissobservator Artikel-Nr.: 1395, see *Figure 11*). The cracks were monitored over a six-month period. No further opening of cracks was noted. On the contrary, the cracks partially closed during the autumn-winter seasons due to the increase in moisture content.

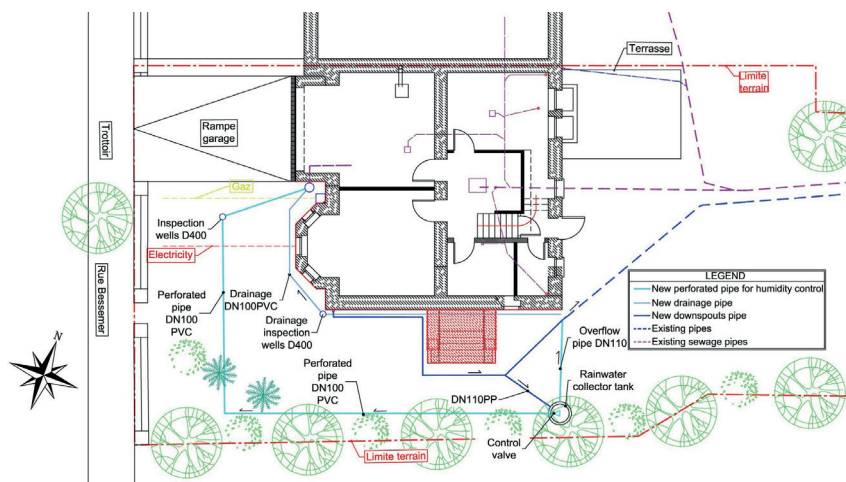


Figure 12: Project plan overview.

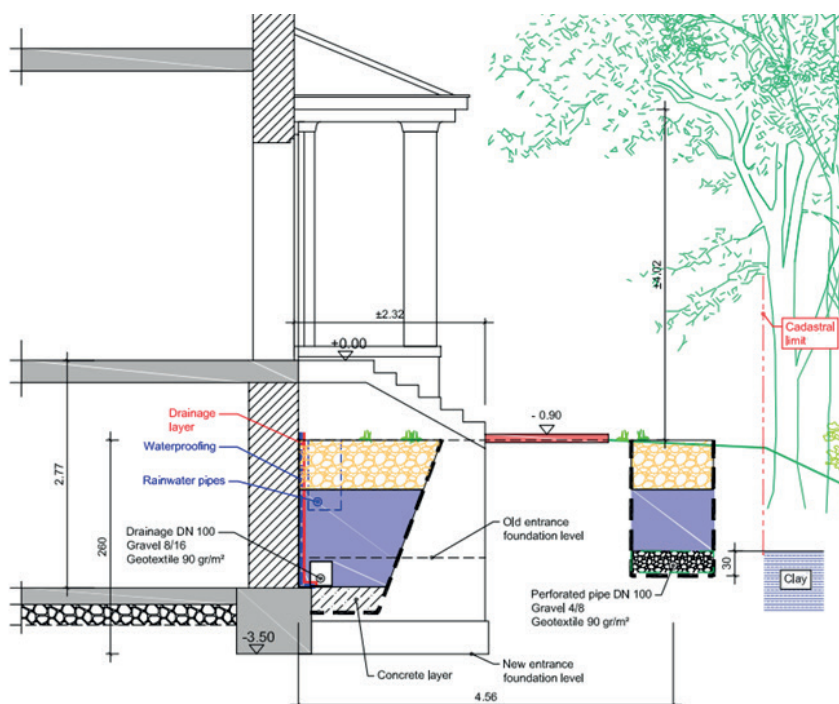


Figure 13: Project section view.

The analysis of the behaviour of the cracks from the crackmeter measurements and the data collected in the geotechnical investigations led to the conclusion that the phenomenon was indeed linked to the shrinkage–swelling of the clays situated at the level of the foundations. The significant evolution and formation of cracks that took place during the year 2018 could be explained partially by the diminishing water balance that characterised the preceding period. Furthermore, the presence of dense vegetation and large trees along the house and the property limits accentuated the problem. Other factors could have been the south-west exposition of the damaged part of the house, which was more subject to the drying process and the downspout malfunction.

The north-east side suffered minor damages overall. The presence of artificial irrigation for the garden and the different exposition positively influenced the behaviour of the soil.

Stabilisation works

The stabilisation works started in June 2020. The objective of the intervention was to protect the soil under the foundations from important changes in the moisture content from the action of the nearby vegetation and drought periods. In order to avoid costly interventions such as a foundation on micropiles or underpinning of the perimeter walls of the house, a less invasive solution was chosen in order to maintain the water content at stable values.

The main measure was the installation of a DN100PVC perforated pipe along the west and south sides at approximately 4.50 m away from the house foundations. The installation depth was set at -2.70 m, on



Figure 14: Stabilisation works: filling of the drainage trench, tank installation, perforated pipe for soil moisture management.

top of the clay layer. The tube was coated with gravel and a non-woven geotextile. Two inspections wells were also installed along the pipe for maintenance purposes. The system is connected on the north-west side of the sewage system to avoid excessive water flow in the soil. In order to provide a renewable water supply, a new rainwater tank collector was installed and connected to the renewed rainwater network. The water flow is controlled by a manual valve installed on the pipe in the tank with an overflow pipe connected to the sewage system installed in the tank to avoid flooding.

In addition to the main stabilisation intervention, secondary measures were carried out. The basement was protected by a waterproofing layer and a drainage layer was installed on the basement wall to divert excess water into a new drainage pipe near the foundations.

The entrance was founded on a more superficial layer (-2.40 m), was thus more sensitive to the shrinkage-swelling phenomenon, as more superficial soil is more affected by variations in the moisture content due to seasonal effects. Consequently, the entrance was demolished and rebuilt with a new foundation at the same level as the building. The project overview is highlighted in *Figures 12 and 13*. Some photos of the intervention are shown in *Figure 14*.

Post-intervention monitoring and results

The crackmeters were monitored during and after the stabilisation works. Figure 15 shows the evolution during the months following the intervention of the most critical crackmeter (No. 5), located at the south-west corner of the building (the most damaged part).

The analysis of the data shows the cracks started closing right after the crackmeter installation (November 2019). This is probably due to a seasonal effect. The perforated pipe for soil moisture control was operational from the end of July 2020. *Figures 15-17* show that between autumn 2020 and February 2022 the crack size has been generally decreasing. Crackmeter No. 1 is less impacted due to its location at the north-east side of the construction, which was less damaged.

Conclusion: the necessity for better management and changing the perception of risk

Clays concern a large part of the territory in places such as Luxembourg and the

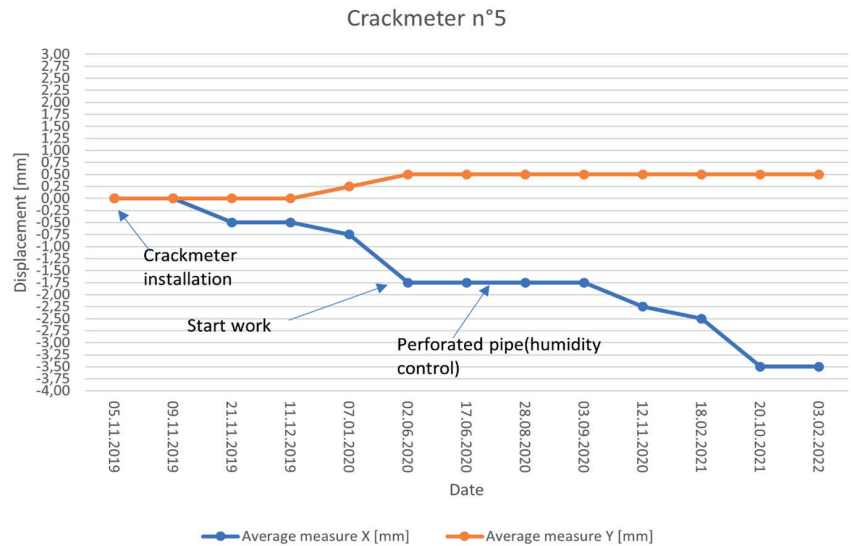


Figure 15: Measurements from crackmeter No. 5 (Nov. 2019 to Feb. 2022).

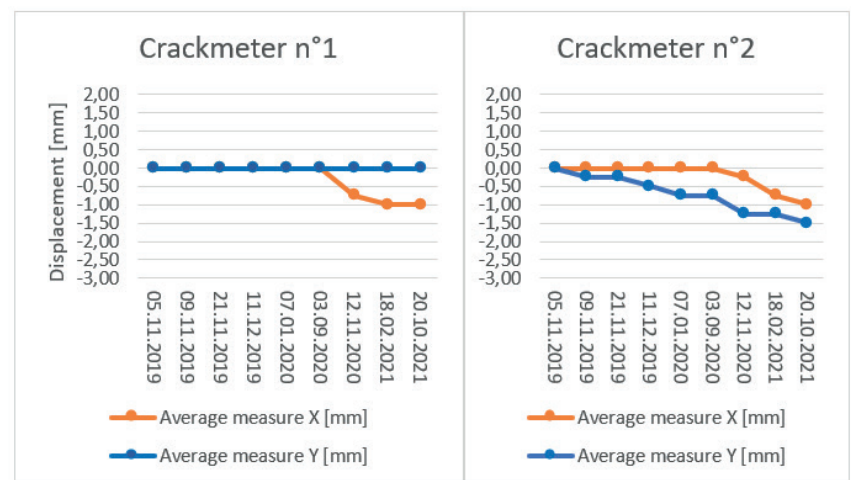


Figure 16: Measurements from crackmeters No. 1 and 2 (Nov. 2019 to Feb. 2022).

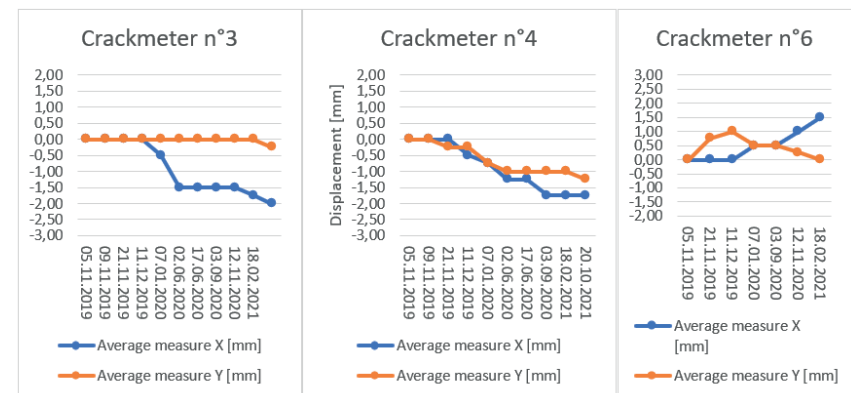


Figure 17: Measurements from crackmeters No. 3, 4, and 6 (Nov. 2019 to Feb. 2022).

phenomenon of the shrinkage-swelling of clays due to variations of soil moisture, which could be further accentuated by climate change, impacts many people and will only increase in the future. The development of technical rules or binding specifications requiring a minimum number of

geotechnical tests to be carried out would make it possible to identify this risk and be able to protect against it. The development of risk maps, which already exist in other countries, would have the advantage of targeting areas at risk and providing easily accessible and interpretable data, even to

non-specialists.

Innovative and more environmentally friendly methods should be developed and promoted from the start of construction projects, in addition with the correct management of rainwater. All of this would allow better management account of the risk by all stakeholders, as well as the limitation of related costs. The maintenance of moisture in the soil near the foundation

could be used in the future to stabilise or prevent possible damage to structure. The relative low cost compared to classical solutions makes this option very attractive. Furthermore, the excess water stored in rainwater tanks could be used for other purposes, like plant irrigation and creating value for the building. The system could be improved by automation, with soil moisture content sensors installed in the bore-

holes or piezometers of the geotechnical survey. The data could be collected in a data logger. Automatic post-processing of the data could warn the user to open or close the water valve. In some systems, such as condominiums, it could be useful to have a smart system with an electromechanical valve in order to make the process completely automatic.

References

Beaufort, D. & Pagel, M. n.d. Structure et propriétés des argiles (Structure and properties of clays), France. Encyclopédie Universalis (online). Accessed 02/02/2022.

<https://www.universalis.fr/encyclopedie/argiles/1-structure-et-proprietes-des-argiles/#DE131166>

Foucault, A. & Raoult, J-F., 2005. Dictionnaire de géologie (Geology Dictionary). 6th edition. DUNOD. Paris.

GSL. 2009. Overview of the Geology of Luxembourg [online], Geological Survey of Luxembourg, Luxembourg. Accessed 27/01/2022]

<https://geologie.lu/index.php/geologie-du-luxembourg/aperçu-geologique/10-overview-of-the-geology-of-luxembourg>

Gruslin, S., 2019. Liaison Esch-Micheville: illustration d'un cas particulier de roche altérée et évolutive: les argilites marneuses du Toarcien (Esch-Micheville connection : illustration of a special case of altered and evolving rock: the bituminous shales of Toarcian). Conference presentation, Construire sur des roches altérées/ évolutives, Journée d'étude de la Société Belge de Géologie de l'Ingénieur et de Mécanique des Roches. 21 November (Building on altered/evolutionary rocks, Study day of the Belgian Society for Engineering Geology and Rock Mechanics).

Houti F.B, undated. Chapitre 2, "Les minéraux et les roches" (chapter 2, Minerals and rocks, in online textbook). Faculty of Technology, Aboubekr Belkaid University, Algeria. Accessed 02/06/2022.

<https://ft.univ-tlemcen.dz/assets/uploads/pdf/departement/gc/houti/Chapitre-2-LES-MINERAUX-ET-LES-ROCHES-2.pdf>

IFSTTAR, 2017. Techniques et Méthodes. Retrait et gonflement des argiles, Caractériser un site pour la construction (Techniques and Methods. Clay shrinkage and swelling, Characterising a site for construction), Guide 1. French Institute of Science and Technology for Transport, Development and Networks.

IFSTTAR, 2017. Techniques et Méthodes. Retrait et gonflement des argiles, Analyse et traitement des désordres créés par la sécheresse (Techniques and Methods. Shrinkage and swelling of clays, Analysis and treatment of disorders created by drought), Guide 3. French Institute of Science and Technology for Transport, Development and Networks.

Lafuerza, S., 2017. Cours de sédimentologie. Chapitre 2 : environnements détritiques (Sedimentology course. Chapter 2: Detrital environments). Université UPMC, Paris.

Luxembourg Agriculture Ministry. 2021. Agri météo, Watterstation Oberkkorn et Remich (Watterstation Oberkkorn and Remich). Ministère de l'Agriculture et de la Viticulture et du développement durable du Luxembourg.

DPPR-SDPRM, 2008. Le retrait-gonflement des argiles. Comment prévenir les désordres dans l'habitat individuel ? (Clay shrinkage and swelling. How to prevent disorders in individual housing?) Collection prévention risques naturels majeurs. Ministère de l'écologie, du développement et de l'aménagement durables : direction de la prévention des pollutions et des risques (DPPR-SDPRM). Paris.

WPW Design Office, 2019. GEOTECHNISCHER BERICHT Nr. (Geotechnical report) Nr. WGL 18.70529-01.

News corner:
Compiled by Anita Stein, EFG Office

EU projects

Horizon 2020 is the biggest EU research and innovation programme ever, with nearly €80 billion of funding available to secure Europe's global competitiveness in

ROBOMINERS



820971 – ROBOMINERS

Resilient Bio-inspired Modular Robotic Miners

START DATE: 1 June 2019

DURATION: 48 months

<http://robominers.eu>

Objectives:

ROBOMINERS will develop a bio-inspired, modular and reconfigurable robot-miner for small and difficult-to-access deposits. The aim is to create a prototype robot that is capable of mining underground, underwater or above water, and can be delivered in modules to the deposit via a large diameter borehole. In the envisioned ROBOMINERS technology

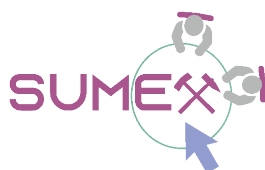
the period 2014–2020. EFG is currently involved in four active Horizon 2020 projects: ROBOMINERS, CROWD THERMAL, REFLECT and SUMEX. In addition, EFG is also participating in two projects

line, mining will take place underground, underwater in a flooded environment. A large diameter borehole is drilled from the surface to the mineral deposit. A modular mining machine is delivered in modules via the borehole. This will then self-assemble and begin its operation. Powered by a water hydraulic drivetrain and artificial muscles, the robot will have high power density and environmentally safe operation. Situational awareness and sensing is provided by novel body sensors, including artificial whiskers, that will merge data in real-time with production sensors, optimising the rate of production and selection between different production methods. The produced high-grade mineral slurry is pumped to the surface, where it will be processed. The waste slurry could then be returned to the mine where to backfill mined-out areas.

under the EIT RawMaterials initiative: ENGIE and PROSKILL. Below you will find descriptions of the topics and aims of these projects.

ROBOMINERS will deliver proof of concept (TRL-4) of the feasibility of this technology line that can enable the EU have access to mineral raw materials from otherwise inaccessible or uneconomical domestic sources. This proof of concept will be delivered in the format of a new amphibious robot Miner Prototype that will be designed and constructed as a result of merging technologies from advanced robotics, mechatronics and mining engineering. Laboratory experiments will confirm the Miner's key functions, such as modularity, configurability, selective mining ability and resilience under a range of operating scenarios. The Prototype Miner will then be used to study and advance future research challenges concerning scalability, swarming behaviour and operation in harsh environments.

SUMEX



101003622 – Sustainable Management in EXtractive industries

START DATE: 1 November 2020

DURATION: 36 months

<https://www.sumexproject.eu/>

Objectives:

SUMEX is a 36-month project funded by the European Commission that started on 1 November 2020. The project supports the set-up of a European sustainability framework to improve the permitting procedure along the extractive value chain (prospecting, exploration, extraction, processing, closure, post-closure activities), to guarantee timely decisions, a transparent governmental regulatory regime, appealing financial and administrative conditions and sustainable natural environmental and social conditions. The main mission of SUMEX is to

assist policymakers and other stakeholders in seizing this opportunity.

In order to foster more extensive but sustainable mineral production in the EU, SUMEX (Sustainable Management in EXtractive industries) will establish a sustainability framework for the extractive industry in Europe. It does so by considering the Sustainable Development Goals, the European Green Deal, as well as EU Social License to Operate considerations and will involve stakeholders from industry, government, academia and civil society backgrounds from all across the EU.

ENGIE



Encouraging Girls to Study Geosciences and Engineering

START DATE: 1 January 2020

DURATION: 36 months

<https://www.engieproject.eu/>

Objectives:

ENGIE aims to turn the interest of 13-to-18-year-old girls towards studying geosciences and related engineering disciplines. As career decisions are generally made in this period of life, the project aims to improve the gender balance in the fields of these disciplines. During the implementation of the three-year-long project an awareness-raising strategy will be developed and an international stakeholder col-

laboration network will be established for the realisation of a set of concrete actions. These actions include family science events, outdoor programmes, school science clubs, mine visits, mentoring programmes, international student conferences, competitions, publication opportunities, summer courses for science teachers and production of educational materials. The actions will be carried out in more than twenty countries throughout Europe.

REFLECT



850626 - Redefining geothermal fluid properties at extreme conditions to optimize future geothermal energy extraction

START DATE: 1 January 2020

DURATION: 36 months

<https://www.reflect-h2020.eu/>

Objectives:

The efficiency of geothermal utilisation depends heavily upon the behaviour of the fluids that transfer heat between the geosphere and the engineered components of a power plant. Chemical or physical processes such as precipitation, corrosion, or degassing occur as pressure

and temperature change, with serious consequences for power plant operations and project economics. Currently, there are no standard solutions for operators to deal with these challenges. The aim of REFLECT is to avoid the problems related to fluid chemistry rather than treat them. This requires accurate predictions and thus a thorough knowledge of the physical and chemical properties of the fluids throughout the geothermal loop. These properties are often only poorly defined, as in situ sampling and measurements at extreme conditions are hardly possible to date. As a consequence, large uncertainties prevail in current model predictions, which will be tackled in REFLECT by collecting new, high quality data in critical areas. The proposed approach includes advanced fluid sampling techniques, the measurement of

fluid properties in in-situ conditions, and the exact determination of key parameters controlling precipitation and corrosion processes. The sampled fluids and measured fluid properties cover a large range of salinity and temperature, including those from enhanced and super-hot geothermal systems. The data obtained will be implemented in a European geothermal fluid atlas and in predictive models that both ultimately allow operational conditions and power plant layout to be adjusted to prevent unwanted reactions before they occur. That way, recommendations can be derived on how to best operate geothermal systems for sustainable and reliable electricity generation, advancing from an experience-based to a knowledge-based approach.

CROWDTHERMAL



857830 - CROWDTHERMAL

Community-based development schemes for geothermal energy

START DATE: 1 September 2019

DURATION: 36 months

<http://crowdthermalproject.eu>

Objectives:

CROWDTHERMAL aims to empower the European public to directly participate in the development of geothermal projects with the help of alternative financing schemes (crowdfunding) and social engagement tools. In order to reach this goal, the

project will first increase the transparency of geothermal projects and technologies by creating one-to-one links between geothermal actors and the public so that a Social Licence to Operate (SLO) could be obtained. This will be done by assessing the nature of public concerns for the different types of geothermal technologies, considering deep and shallow geothermal installations separately, as well as various hybrid and emerging technology solutions. CROWDTHERMAL will create a social acceptance model for geothermal energy that will be used as baseline in subsequent actions for inspiring public support for geothermal energy. Parallel and synergetic with this, the project will work out details of alternative financing and risk mitiga-

tion options covering the different types of geothermal resources and various socio-geographical settings. The models will be developed and validated with the help of three case studies in Iceland, Hungary and Spain and with the help of a Trans-European survey conducted by EFG Third Parties. Based on this feedback, a developers' toolbox will be created with the aim of promoting new geothermal projects in Europe supported by new forms of financing and investment risk mitigation schemes that will be designed to work hand in hand with current engineering and microeconomic best practices and conventional financial instruments.

PROSKILL



Development of a Skill Ecosystem in the Visegrád Four countries

START DATE: 1 January 2020

DURATION: 36 months

www.proskillproject.eu

Objectives:

The European Union puts emphasis on raising productivity as an important factor in maintaining economic growth. In order to improve productivity, it is vital to offer products and services with a high

added value, and for that purpose highly qualified employees are required. Companies and professional organisations in the raw materials industries have stressed the need to improve the soft skills of students in order to meet the requirements of the labour market. The engineers of the future have to accept that engineering problems – as well as their solutions – are embedded in complex social, cultural, political, environmental and economic contexts. Engineers have to access, understand, evaluate, synthesise, and apply information and knowledge from engineering as well as from other fields of study. They have to find and achieve a synergy between technical and social systems. ProSkill has a double purpose. From the one side it adopts a 'skill

ecosystem' concept, looking at what (hard and soft) skills are missing in the raw materials sector, which areas are affected by skill problems (shortages, mismatches and gaps) and what strategies can work. A high-skill ecosystem strategy supplemented with an action plan is developed. To ensure sustainability, the project focuses on lecturers in higher education ('train the trainer'). The main goal is to develop their knowledge about new and innovative educational techniques and to reshape outdated curricula. On the other side, a pilot project is launched involving the colleges for advanced studies in partner HEIs. Short-term and long-term programmes help to implement the strategy with the targeted development of selected soft skills.

Submission of articles to European Geologist Journal

Notes for contributors

The Editorial Board of the European Geologist journal welcomes article proposals in line with the specific topic agreed on by the EFG Council. The call for articles is published twice a year in December and June along with the publication of the previous issue.

The European Geologist journal publishes feature articles covering all branches of geosciences. EGJ furthermore publishes book reviews, interviews carried out with geoscientists for the section 'Professional profiles' and news relevant to the geological profession. The articles are peer reviewed and also reviewed by a native English speaker.

All articles for publication in the journal should be submitted electronically to the EFG Office at info.efg@eurogeologists.eu according to the following deadlines:

- Deadlines for submitting article proposals (title and content in a few sentences) to the EFG Office (info.efg@eurogeologists.eu) are respectively 15 July and 15 January. The proposals are then evaluated by the Editorial Board and notification is given shortly to successful contributors.
- Deadlines for receipt of full articles are 15 March and 15 September.

Formal requirements

Layout

- Title followed by the author(s) name(s), place of work and email address,
- Abstract in English, French and Spanish,
- Main text without figures,
- Acknowledgements (optional),
- References.

Abstract

- Translation of the abstracts to French and Spanish can be provided by EFG.

- The abstract should summarise the essential information provided by the article in not more than 120 words.
- It should be intelligible without reference to the article and should include information on scope and objectives of the work described, methodology, results obtained and conclusions.

Main text

- The main text should be no longer than 2500 words, provided in doc or docx format.
- Figures should be referred in the text in italic.
- Citation of references in the main text should be as follows: 'Vidas and Cooper (2009) calculated...' or 'Possible reservoirs include depleted oil and gas fields...' (Holloway *et al.*, 2005). When reference is made to a work by three or more authors, the first name followed by 'et al.' should be used.
- Please limit the use of footnotes and number them in the text via superscripts. Instead of using footnotes, it is preferable to suggest further reading.

Figure captions

- Figure captions should be sent in a separate doc or docx file.

References

- References should be listed alphabetically at the end of the manuscript and must be laid out in the following manner:
- Journal articles: Author surname, initial(s). Date of publication. Title of article. Journal name, Volume number. First page - last page.
- Books: Author surname, initial(s). Date of publication. Title. Place of publication.
- Measurements and units
- Measurements and units: Geoscientists use Système International (SI) units. If the measurement (for example, if it was taken in 1850) was not in SI, please convert it (in

parentheses). If the industry standard is not SI, exceptions are permitted.

Illustrations

- Figures should be submitted as separate files in JPEG or TIFF format with at least 300dpi.
- Authors are invited to suggest optimum positions for figures and tables even though lay-out considerations may require some changes.

Correspondence

All correspondence regarding publication should be addressed to:

EFG Office

Rue Jenner 13, B-1000 Brussels, Belgium.

E-mail: info.efg@eurogeologists.eu

Note

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Advertisements

EFG broadly disseminates geology-related information among geologists, geoscientific organisations and the private sector which is an important employer for our professional members, but also to the general public.

Our different communication tools are the:

- EFG website, www.eurogeologists.eu
- GeoNews, a monthly newsletter with information relevant to the geosciences community.
- European Geologist, EFG's biannual journal. Since 2010, the European Geologist journal is published online and distributed electronically. Some copies are printed for our members associations and the EFG Office which distributes them to the EU Institutions and companies.

By means of these tools, EFG reaches approximately 50,000 European geologists as well as the international geology community.

With a view to improving the collaboration with companies, EFG proposes different advertisement options. For the individual prices of these different advertisement options please refer to the table.

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Ad and regular newfeed

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1500 Euro

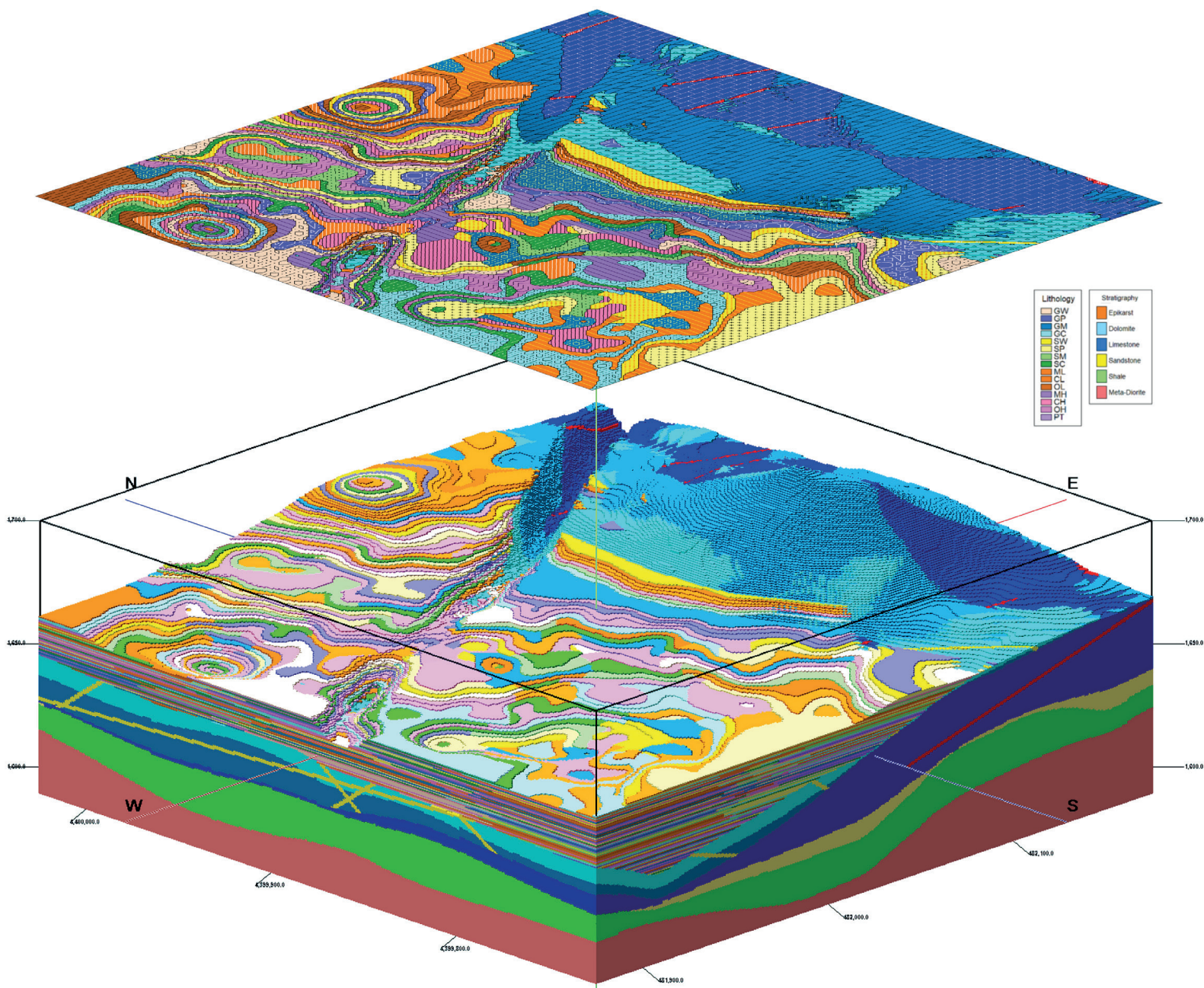
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